Investigating the Earth

Revised Edition / American Geological Institute

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Investigating the Earth

Revised Edition

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Miles F. Harris

Dale T. Hesser

J. Allen Hynek

William H. Matthews, III

Chalmer J. Roy

James W. Skehan, S.J.

Robert E. Stevenson

Sponsored by the American Geological Institute and based on the original Earth Science Curriculum Project.

Authors

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Maps on pages 220, 221, 404, and 405 are rendered by Lilli Tanzer in INTRINSICOLOR.

Preface to the First Edition

We would like to tell you how this book came about. Hundreds of people worked more than three years to prepare it. Why were so many people involved? Why did the work take so long?

The scientists and educators who planned *Investigating the Earth* wanted many different persons to be involved. They sought the help of scientists in many fields to make sure that the basic principles in all these fields formed an integrated and up-to-date story of planet earth and its environment in space. They wanted advice from teachers using the book about how young people could best investigate and learn. Finally, they wanted the reactions and opinions of students like yourself — what was exciting for them and what helped them to learn.

At the beginning of this project, a planning group prepared an outline for a science book that would encompass the story of the planet earth. They then invited 40 scientists and teachers to meet and write a first version of the book. Astronomers, geologists, geographers, geophysicists, meteorologists, oceanographers, soil scientists, science educators, and teachers came to Boulder, Colorado to prepare manuscript for the book.

The first version of *Investigating the Earth* was sent to 77 teachers in schools across the country. During that first year it was used by 7,500 students. Each week the teachers sent their comments and the comments of their students back to the ESCP staff. The following summer another group of writers assembled in Boulder to write a second version of the Text. Changes in that Text were based on the reactions of the teachers and students who had used the book. The second version was also evaluated in many schools and involved thousands of students. The comments of teachers and students were gathered each week, studied, and used to prepare the third and final version of the book during the spring and summer of 1966. This is the book you are now reading. The many people involved in its preparation hope that their efforts have produced a stimulating book, one that will make your investigation of the earth more interesting.

The contents of this book may raise many new questions in your mind. You will answer some of these questions yourself by observing and performing investigations. Some will be answered in the Text and others by your teacher. Many will remain unanswered. When you read newspapers and magazines you find that you are not alone in wondering about these unanswered questions. Thousands of people such as scientists, philosophers, and teachers are constantly inquiring into the unknown.

Although basic principles are modified slowly, many of the ideas presented in this book are changing rapidly as man expands his knowledge. You will find it interesting to understand and keep pace with these advances. The people who worked on *Investigating the Earth* have attempted to give you some of the exciting developments in earth science by letting you find answers for yourself. They hope that in this way you may better appreciate future discoveries and perhaps participate in them yourself.

Ramon E. Bisque
Robert L. Heller

Preface to the Revised Edition

The authors of this edition of *Investigating the Earth* were part of the team that wrote the original edition. We gladly acknowledge our debt to our associates, who developed a new kind of earth science text. Never before had so many specialists joined in a common effort. They did not follow the traditional practice of teaching oceanography, geology, astronomy, biology, meteorology, and geography as separate and isolated studies. Instead, they were pioneers in unifying these various sciences into one earth science. We have tried to preserve their approach, while bringing the text up-to-date with recent discoveries about the earth, the moon, and the universe.

The authors hope that the study of this book will lead you to a concept of science like that stated recently by Warren Weaver, a famous researcher: "Science is not technology, it is not gadgetry, it is not some mysterious cult, it is not a great mechanical monster. Science is an adventure of the human spirit. It is essentially an artistic enterprise stimulated largely by curiosity, served largely by disciplined imagination, and based largely on faith in the reasonableness, order, and beauty of the universe of which man is a part."

Science is not a body of knowledge but a means of winning knowledge from ignorance. It is most of all a way of life and an unfinished human enterprise.

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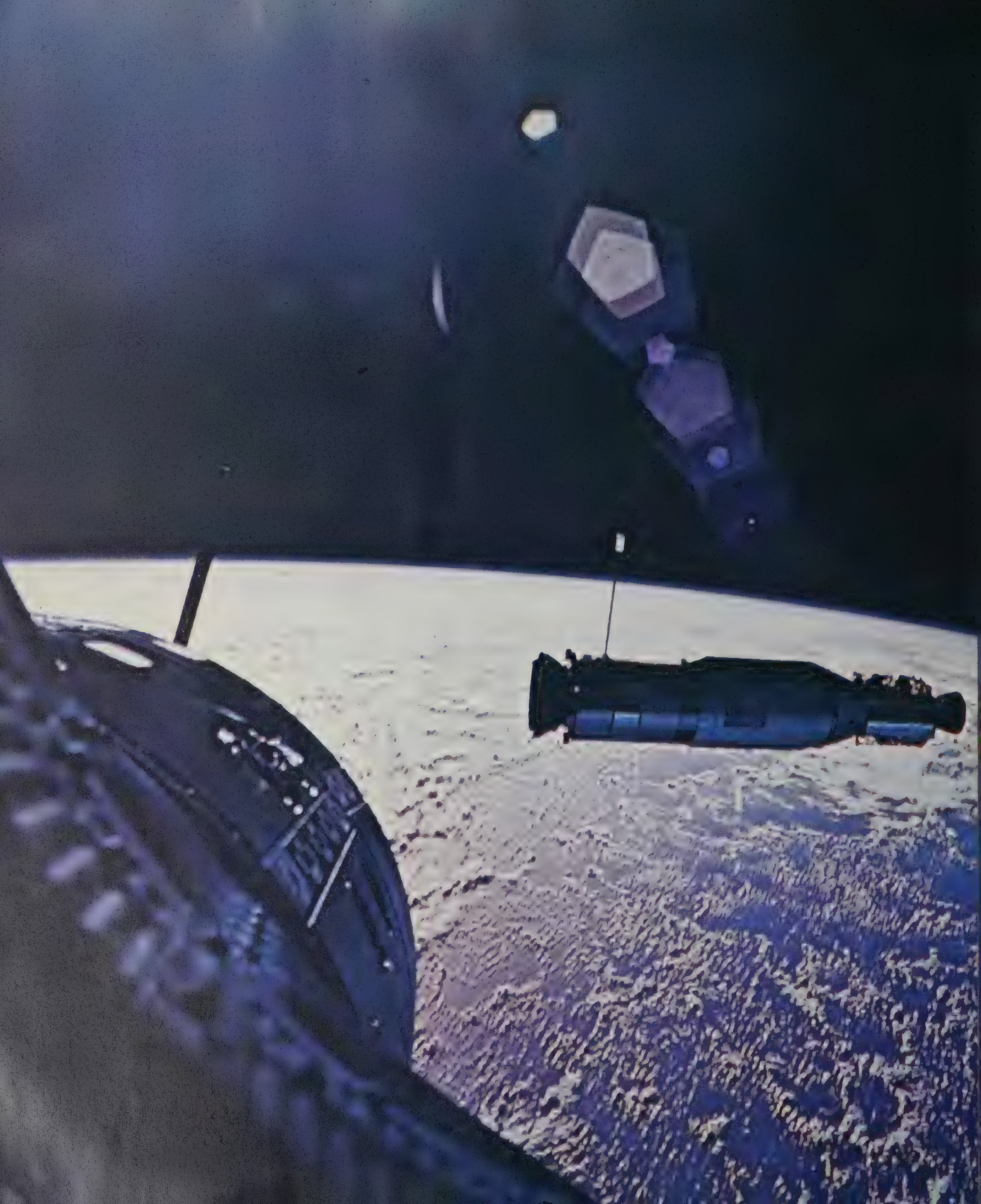


unit one

The Dynamic Earth

1. The Earth and Moon in Space

Some of the most thrilling photographs ever taken are the first pictures of the earth as seen from outer space. The one you are looking at was taken by a rocket orbiting the moon. The photo shows the surface of the moon looming in the foreground and way off in the distance, a tiny moon-like object—the earth!

No national boundaries or artificial separations can be seen. It is all one world. For the first time man was able to see his home in space, the earth, from outside.

Do you usually think of the entire planet as "home"? Does it seem sensible or not to talk that way?

A young man in a novel gives his "home address" as:

Stephen Dedalus
Clongowes Wood College
Sallins
County Kildare
Ireland
Europe
The World
The Universe

What do you think of as your home? Is it the house you live in, the people you live with, or all the things that surround you?

It might be interesting for people to compare their definitions of home with each other, now and at the end of this course. Put the word **me** *in the center of a large sheet of paper. Then, use the rest of the paper to write or draw the important parts of your environment.*

The Earth's Size and Motions

1–1
The view from space

When the astronauts described the earth from space, they saw it as a water- and cloud-covered sphere, turning constantly under the sun's rays. They were able to see parts of both the daylight and night sides of the earth. It appeared to have "phases" like the moon—"full earth," or "first-quarter earth," and so on, as in Figure 1–1.

Some day astronauts will venture farther out into space on their way to the other planets. They will be able to get still more distant views of our planet earth. They will see that the earth is not alone in space, but that together with the moon, it looks more like a "double planet."

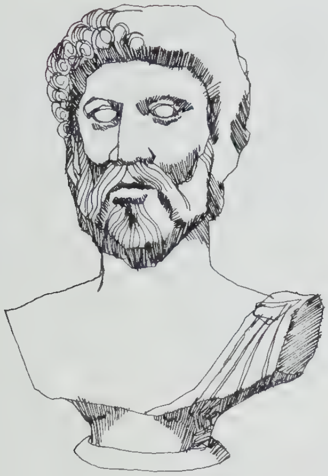
1–2
Measuring the earth

Two thousand years ago, when a hundred kilometers was a long journey, Eratosthenes (eh-rah-TOS-thah-neez), a Greek astronomer, used some simple principles of geometry to estimate the size of the earth. This investigation uses his idea. Try it and see how it works.

Procedure

*Estimate the angle **a** of the shadow cast in your school yard at midday by a stick placed straight up in the ground. (See Figure 1–2.) Copy Figure 1–3, using your own measured angle. Show on the diagram where you would place a vertical stick that would cast no shadow.*

Figure 1–1
What is the phase of the earth in each of these pictures?



This Greek geographer (about 276–194 B.C.) made a surprisingly accurate estimate of the earth's circumference. In the great library in Alexandria he read about a deep vertical well near Syene in southern Egypt. The well was entirely lit up by the sun at noon once a year. Eratosthenes reasoned that at this time the sun must be directly overhead, with its rays shining straight into the well. Alexandria is almost 1,000 kilometers due north of Syene. He knew that in Alexandria at noon on that same day a vertical object cast a shadow. Therefore, the sun was not directly overhead there.

Eratosthenes could now measure the circumference of the earth by making two assumptions—that the earth is round and that the sun's rays are essentially parallel. He set up a vertical post at Alexandria and measured the angle of its shadow when the well at Syene was completely sunlit. Eratosthenes knew from geometry that the size of the measured angle equaled the size of the angle at the earth's center between Syene and Alexandria.

The angle was 1/50 of a circle, and the distance between Syene and Alexandria was 5,000 stadia. He multiplied 5,000 by 50 to find the earth's circumference. His result of 250,000 stadia (about 46,250 km) is close to modern measurements.

FIGURE 1–2

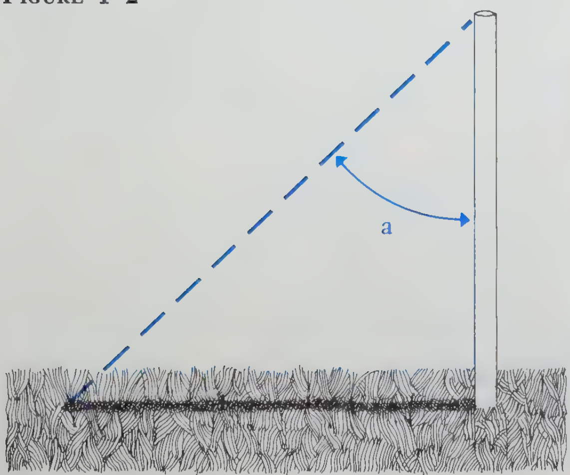
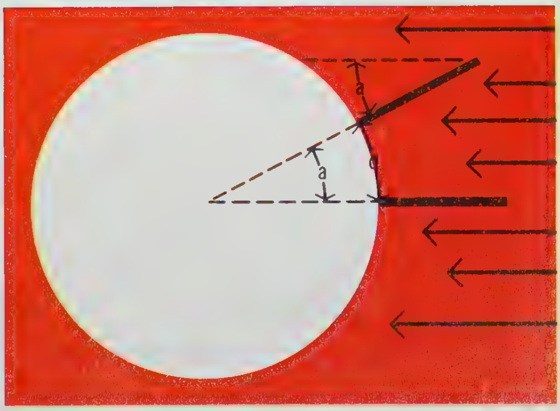


FIGURE 1–3



You can calculate the circumference of the earth if you know the distance, d, between the two sticks on the real world and the angle of the cast shadow ***a***. You can find the distance on the plastic globe provided for you.

Set up the plastic globe and the sticks with suction cups to look like your diagram. Measure the distance between the sticks, using the ruler provided. It is calibrated so that distances on the plastic globe in millimeters stand for distances on the earth in kilometers.

Use this formula to calculate the circumference of the earth:

$$\frac{\text{Distance around globe}}{\text{distance between sticks}} = \frac{360^\circ}{\text{angle } \boldsymbol{a}}$$

$$\text{or } \frac{D}{d} = \frac{360^\circ}{\boldsymbol{a}}$$

*This ratio can be stated as follows: Part of the distance around the globe is to the entire distance as angle **a** is to the angle of the full circle.*

How close is your calculated circumference of the earth to the value given in Figure 1–4?

1–3 How do you know that the earth rotates?

From Mars, astronauts could see the moon circling the earth, and the earth and moon together going around the sun. To be more exact, they would see that the moon and earth swing *around each other*. They are like two children,

FIGURE 1–4
Dimensions of the Earth

DIMENSIONS	ACCEPTED VALUE	
	Kilometers	*Miles*
EQUATORIAL RADIUS	6,378	3,964
POLAR RADIUS	6,357	3,950
EQUATORIAL CIRCUMFERENCE	40,076	24,902
POLAR CIRCUMFERENCE	40,008	24,860

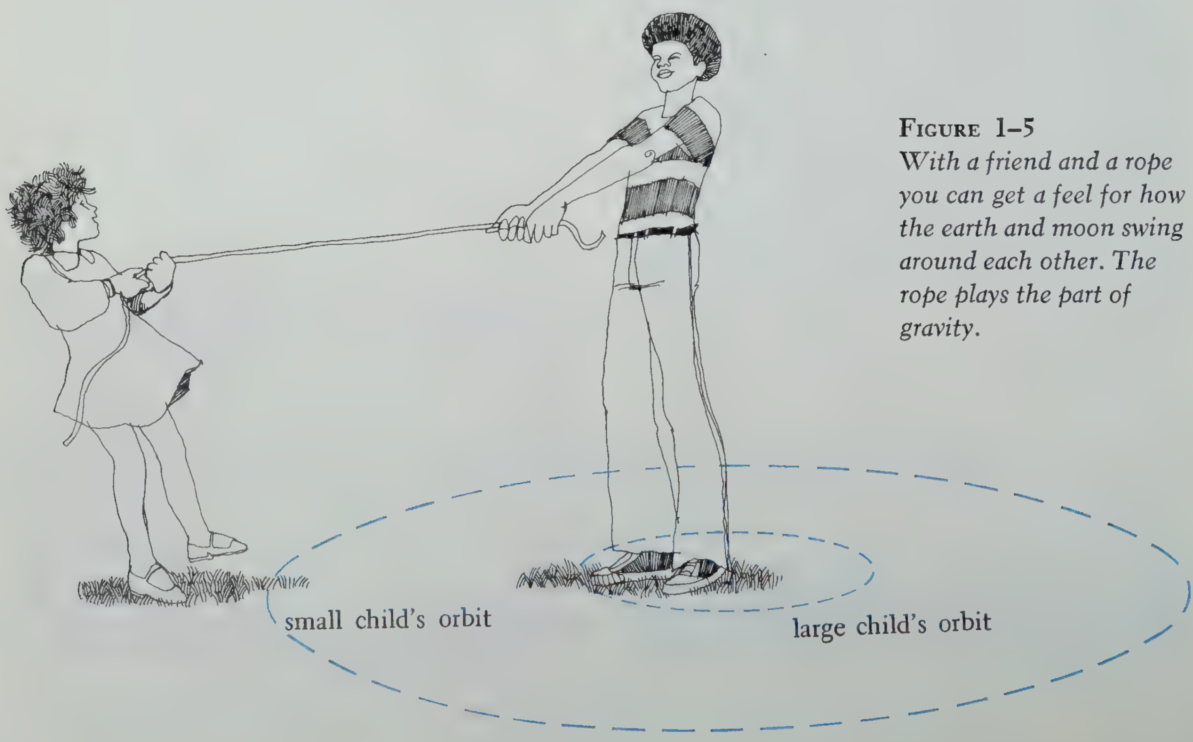


FIGURE 1–5
With a friend and a rope you can get a feel for how the earth and moon swing around each other. The rope plays the part of gravity.

one heavy, the other light, holding onto a rope and swinging around (Figure 1–5). The small child (the moon) swings in a much wider arc because she is lighter. One might almost say that the big child is standing still, but in fact he is not.

In the same way, we say the moon goes around the earth, but actually both go around a common point. Because the earth is 81 times more massive than the moon, this pivot point is actually located about 1,000 miles *below* the earth's surface. This common point (called the **barycenter**) sweeps around the sun once a year. Its path makes the smooth orbit that is shown in Figure 1–6.

Viewed from a few million miles out in space, there is no need to prove that the earth rotates on its axis, or revolves about the sun, or that the moon travels around the earth. All one has to do is look!

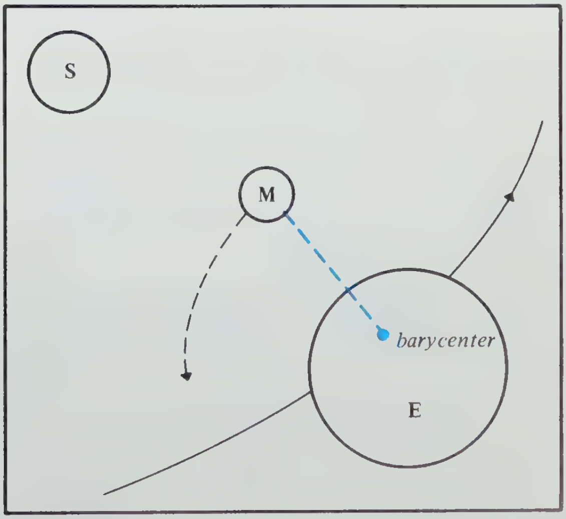
But we are not astronauts, and here on the surface of the earth our perspective is lost. The motions of the earth are so smooth that we don't feel or see them. Until the coming of the space age it was necessary to devise proofs that the earth moves. That was not easy. Suppose you were offered a big prize to prove that the earth turns on its axis. Would you be able to do it?

1–4 Proving that the earth rotates

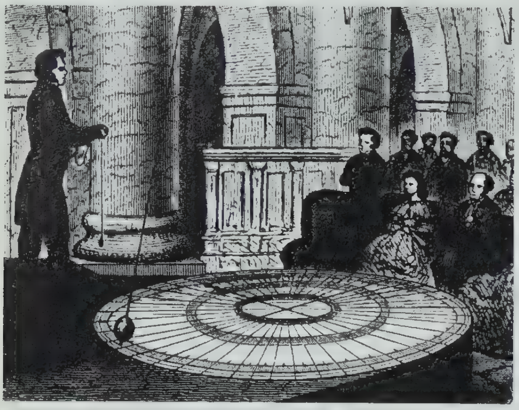
The fact that we have day and night is not a proof. The ancient Greeks and Romans explained day and night by having the sun go around the earth once a day. An experiment that showed the earth's rotation was devised by the French physicist Foucault.

Think of a pendulum that is free to swing in every possible direction. If it is set to swing in a certain direction, the pendulum will maintain that direction of swing in space.

Figure 1–6
The barycenter orbits the sun in an elliptical path. Do you think it has a fixed location within the earth?



JEAN FOUCAULT



This French scientist (1819–1868) invented the gyroscope. He also accurately measured the speed of light and devised the first practical demonstration of the earth's rotation.

The Foucault pendulum, was suspended from the ceiling of the dome of the Pantheon in Paris. It was a cannon ball hanging from a 219-foot wire, its upper end fastened to a freely rotating swivel.

The great pendulum came within inches of the Pantheon floor. When Foucault set the ball in motion, a thin pointer attached to it traced the path of its swing in a layer of sand. It was known that a swinging pendulum would move in a constant plane unless deflected by some outside force. Amazingly, the Foucault pendulum slowly rotated at the rate of 360 degrees in about 31 hours. Scientists of Foucault's day knew that the earth turned on its axis, but they had never seen such a clear demonstration.

Figure 1–7
What is changing direction, the pendulum or the house at the North Pole?

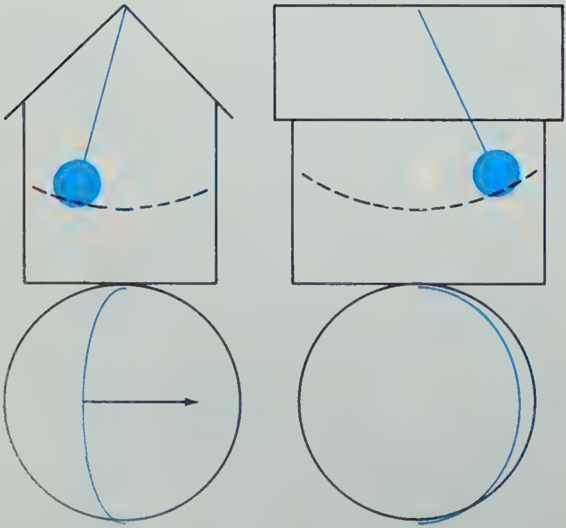
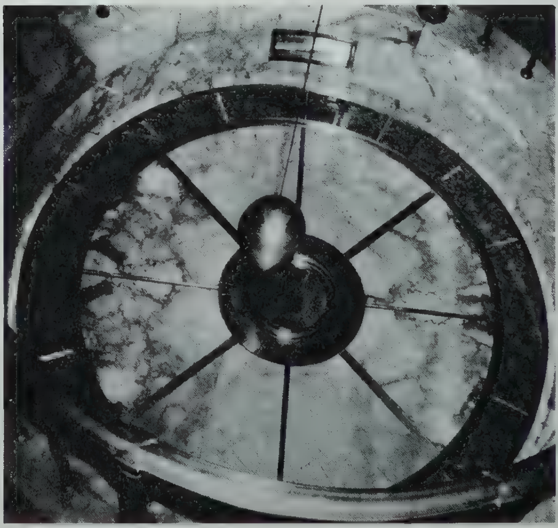


Figure 1–8
Foucault Pendulums like this one are actually kept swinging by a small motor.



Put a pendulum in a house exactly at the North Pole. Because the earth is turning, the house also turns once during 24 hours. You would not be aware that the house was turning, but you would see the pendulum slowly change its direction of swing, as in Figure 1–7. It might seem an eerie sight.

The experiment was never performed at the North Pole, but it was performed in Paris in 1842. Away from the Pole the direction of the pendulum swing changes more slowly, but it still demonstrates the rotation of the earth very well. Most planetariums and museums have a Foucault pendulum like the one in Figure 1–8. Try to see one in operation.

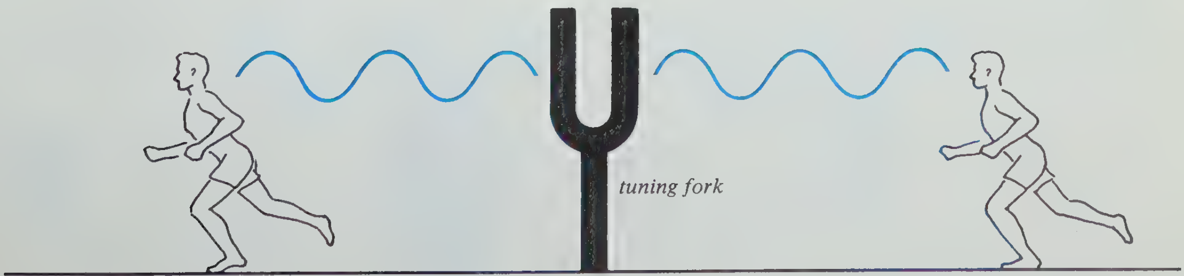
1–5 The earth revolves around the sun.

The earth's yearly journey around the sun can be proved in several ways. We'll examine only one interesting proof, based on the "Doppler effect." You may have noticed that the sound of a horn or whistle moving rapidly toward you seems to have a higher pitch while approaching, and a lower pitch when moving away. This is known as the **Doppler effect**. (See Figure 1–9.) It happens whenever you and a source of sound are moving away from or toward each other.

Light is also affected by motion. Light from an object moving toward you appears bluer, whereas light from an object moving away from you appears redder. Unless the speeds are very great, though, the shift in color is too slight for the eye alone to see. An instrument called the **spectrograph** is used. It forms a spectrum of the light passing through it, and photographs it. When light from a star is examined with a spectrograph, very slight changes in color can be detected. The relative speed of the star towards or away from us can then be found.

Now, if the earth travels around the sun, it must be moving toward stars in one part of the sky and away from stars in the opposite region of the sky. (See Figure 1–10.) The spectrograph does indeed show that the light from the stars the earth is approaching is slightly bluer than light from the stars in the opposite part of the sky—stars the earth is going away from at the moment.

Figure 1–9
When the man runs away from the tuning fork, fewer sound waves reach his ear each minute. The pitch of the tuning fork seems lower. What happens when he runs toward the tuning fork?



Of course, six months later, when the earth is at B (Figure 1–10) just the opposite happens. The stars whose light was slightly bluer are now slightly redder. The speed needed to cause this shift turns out to be about 30 kilometers per second. This is the earth's average speed as it circles the sun. How many kilometers an hour is that?

1–6 The seasons

If the earth's axis were not tipped, each hemisphere would receive the same amount of sunlight at all times. Days would always be 12 hours long at the equator and 24 hours long at the poles. And there would be no seasons. But the earth's poles are tipped away from the vertical by 23½ degrees.

When the earth is at position D in Figure 1–11, the North Pole of the earth gets no daylight at all while the South Pole has 24 hours of daylight. Position D marks the beginning of winter in the Northern Hemisphere. The nights are longer than the days in the winter season. The situation is reversed six months later when the earth is at position B. Summer then begins in the Northern Hemisphere, and the days are longer than the nights.

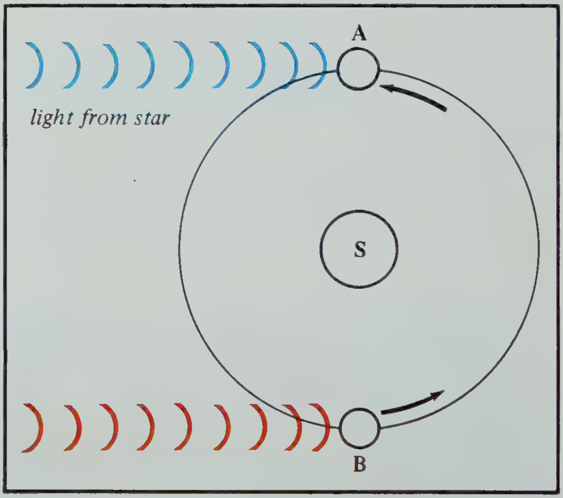
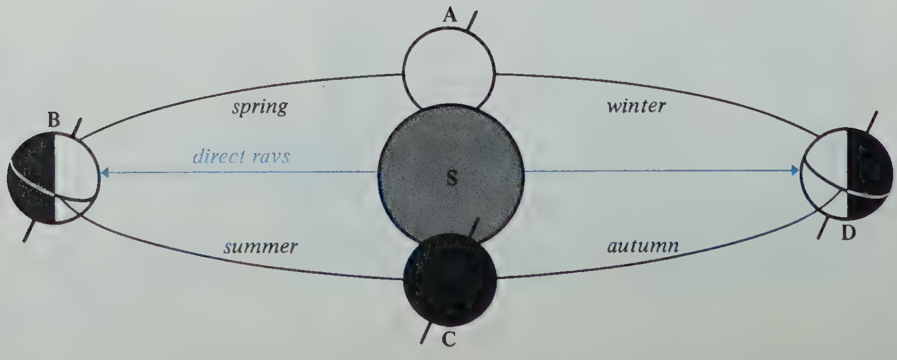


Figure 1–10
Using a spectrograph at points A and B, we can detect a difference between the light from distant stars.

Figure 1–11
The positions of the earth and sun at (A) March 21, (B) June 21, (C) September 21, and (D) December 21. In the Southern Hemisphere what season begins on September 21?



From Figure 1–11 you can see that when the earth is near B the direct sun rays strike the earth north of the equator. Therefore, more heating occurs. When the earth is near D, the most direct rays of the sun fall south of the equator. Now the Southern Hemisphere has summer.

On December 22 the North Pole is tipped farthest away from the sun. Even though winter begins on December 22 in the Northern Hemisphere, it is not the coldest time of year. At the same time, the South Pole is getting the most sunlight it ever gets. But summer is only beginning in the Southern Hemisphere.

To understand this situation, think of one person just leaving a warm house and another person just entering the house from the cold outside. Imagine that they meet in the doorway. Since they're standing in the same place, you might expect them to be at the same temperature. But this is not so. One has been in a warm room; his body and clothes have stored warmth. He will not begin to feel really cold until he has been outside for a while. The person coming in from the cold will not feel warm until he has been inside by the fire for a few minutes.

It is the same with the seasons. On December 22, the sun is lowest in the sky and the nights are longest, but the Northern Hemisphere has stored heat from the summer just past. We don't feel the cold of deep winter until mid-January and February. Similarly, the Northern Hemisphere receives the most heat and light from the sun on June 21, when the sun appears highest in the sky. But we don't feel the full warmth of summer until July and August. Then we have had a chance to shake off the cold of winter and spring. Thus, the seasons lag a month or so behind the sun.

As we go about our daily work and play, the earth seems stationary and flat. We do not realize that in reality we are on a spinning, revolving ball of matter, moving rapidly through space. As the earth rotates on its axis, it alternately turns us toward and away from the sun, giving us night and day. As it revolves around the sun, it presents its Northern and Southern Hemispheres alternately to the more direct rays of the sun. This gives us the seasons and influences the lives of plants and animals. What would our lives be like if there were no seasons?

In the next investigation you will see for yourself just how much the sun's position in the sky varies.

1–7
Investigating the sun's path—Sun Watch

Many of the changes of position of the sun and other celestial objects are called ***apparent*** *changes. This is because the change we see is not actually taking place. An example is the apparent rising and setting of the sun. Actually, these changes are caused by the turning of the earth. We know that the sun does not really rise and set, but only appears to do so. Other changes in the sky are real and not just apparent. The* ***eastward*** *motion of the moon among the stars is a good example.*

To investigate the changes in the sun's path in the sky, you must plot the sun's daily path several times during the year. It is important

that you start these observations now so that you can compare them with observations made weeks and months later.

PROCEDURE

Using the plastic hemisphere and globe as shown in Figure 1–12, plot the position of the sun in the sky several times during the day. Start as early in the school day as possible, when the sun is far in the east. Make your last observation late in the afternoon, when the sun is far in the west. When you connect all the points you have plotted, you will have a record of the path the sun made on the sky that day. ***Keep this record for future use.*** *You will compare the sun's path in the sky now with its path at other times of the year. Plot the sun's path again on or near the following eight dates: October 20, November 20, December 22, January 20, February 20, March 20, April 20, and May 15.*

Thought and Discussion

1. If our skies were always cloudy, do you think we could prove that the earth rotates? Do you think we could prove it was round?
2. Does it seem strange to you that the barycenter is *inside* the earth? Since the earth is turning on its axis, does this mean that at one time of day the barycenter is under the Atlantic Ocean, and 12 hours later under the Pacific?
3. How could a person be thirteen years old and yet have lived through sixteen summers?
4. What daily paths of the sun do you think you would draw if you conducted your Sun Watch at the equator? At the North Pole? Would a person at the North Pole ever see a sunset?
5. Can you figure out why the Foucault pendulum will not rotate at the equator?
6. From the earth's speed around the sun (30 kilometers per second) can you figure out how far we are from the sun? Hint: There are about 31 million seconds in a year.
7. What sort of seasons would there be if the earth's axis were tipped 90 degrees instead of only 23½ degrees?

FIGURE 1–12
How can the position of the base affect the path that you plot on the plastic hemisphere?

The Moon, our Natural Satellite

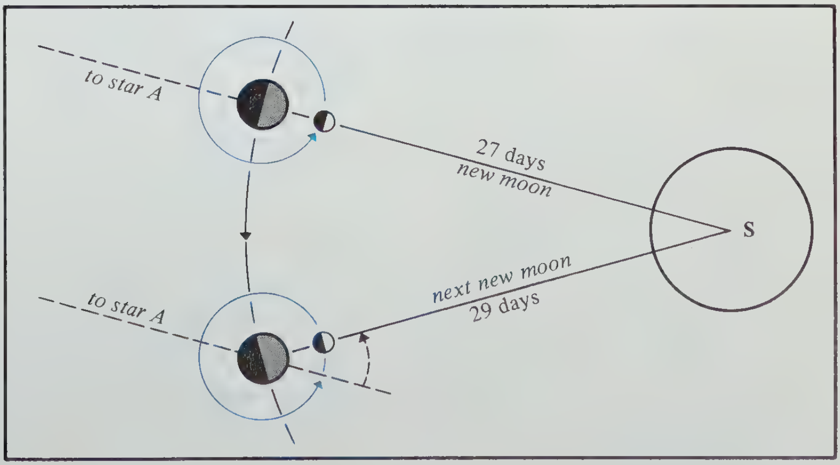
1–8
The moon in motion

We can plot moon-motion around the earth by looking at it day and night from the surface of the earth. The moon appears to rise and set, as the sun does, because the earth is turning. It also has a real motion. Each night, the moon appears about 13 degrees farther east in the sky than the night before. That is about the arc of sky covered by an outstretched hand. In this way, the moon goes completely around the sky in a little more than 27 days. But as any calendar will tell you, from one full moon to the next full moon averages more than 29 days. Why the difference? While the moon is going around the earth, the earth is going around the sun. Figure 1–13 shows how this difference arises.

We know the sun is in the sky by its outpouring of light and heat, but it is too bright to look at directly. The moon is different. We can watch it for long periods of time. While it does not affect our daily lives as strongly as the sun does, it does so in gentler ways. It is the prime mover of our tides. (The sun affects the tides, too, but not as much as the moon does.) Some people think that the moon even influences our feelings. The word "lunacy" comes from Luna, one of the many names for the moon. Selene, Diana, and Cynthia are others. Can you imagine any reasons why ancient peoples thought the moon was a goddess?

Figure 1–14
The highest tides on earth occur at the Bay of Fundy in Nova Scotia.

Figure 1–13
How long is a month on the moon?



1–9
The tides

For those who live and work near the seashore, the tides are very important. It was long known from simple observation that the tides in some way depended on the moon. But it was not known exactly how, nor why there were two high tides a day along most coasts instead of just one.

If you join hands with a friend and swing around quickly, you will notice a pull outward, away from each other. If you were to let go suddenly, you would tumble backwards. This outward pull is called a **centrifugal force.**

When the earth and moon swing around each other, they experience a similar outward pull. But this force is balanced by a gravitational pull. At the center of the earth the two forces are equal (Figure 1–15). At point A, nearest the moon, the gravitational pull is greater than the centrifugal force. Liquid water is free to flow, but the solid earth isn't. The water piles up in a "hill." This hill is the high tide on the side of the earth that is nearest the moon.

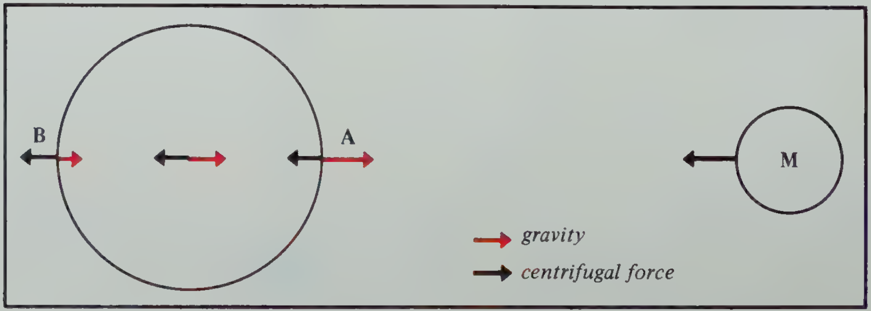
There is also a high tide on the opposite side of the earth. At point B in Figure 1–15, the pull from the moon is weaker than the centrifugal force. The water "swings away" from the earth, causing a second high tide.

1–10
Phases of the moon

The phases of the moon are caused by the changing positions of the earth, moon, and sun. The moon has no light of its own and shines by reflected sunlight. One half is always lighted by sunlight, just like the earth. At one time of the month, when the moon is at position A in Figure 1–16, the lighted side of the moon is the side facing away from the earth. The side facing us is dark. This phase is called **new moon** because the new cycle of phases is about to start.

A few days later (position B), most of the lighted side is still turned away from us, but a small portion of it is visible. We see that portion as a **crescent.** Seven days after new moon, the moon is in position C. We can then see one-half of the half of the moon that is illuminated. We call this phase **first quarter.**

FIGURE 1–15
High tides are created because the force of gravity and the centrifugal force are unequal at points A and B. What causes the high tides to move around the earth?



When the moon is at D, the side which always faces us is fully lighted. This is **full moon.** Of course, to see the fully lighted side of the moon, we must be between the sun and the moon. The full moon rises, therefore, as the sun sets, since they are in opposite parts of the sky.

Seven days after full moon, the moon is at E, and the side facing us is half light and half dark. This phase is called **last quarter.** The moon in last quarter rises at midnight. Each night after that it swings closer and closer to the sun in the sky, finally rising just before the sun does. We see it then as a crescent (F), since almost all of the lighted side is turned away from us.

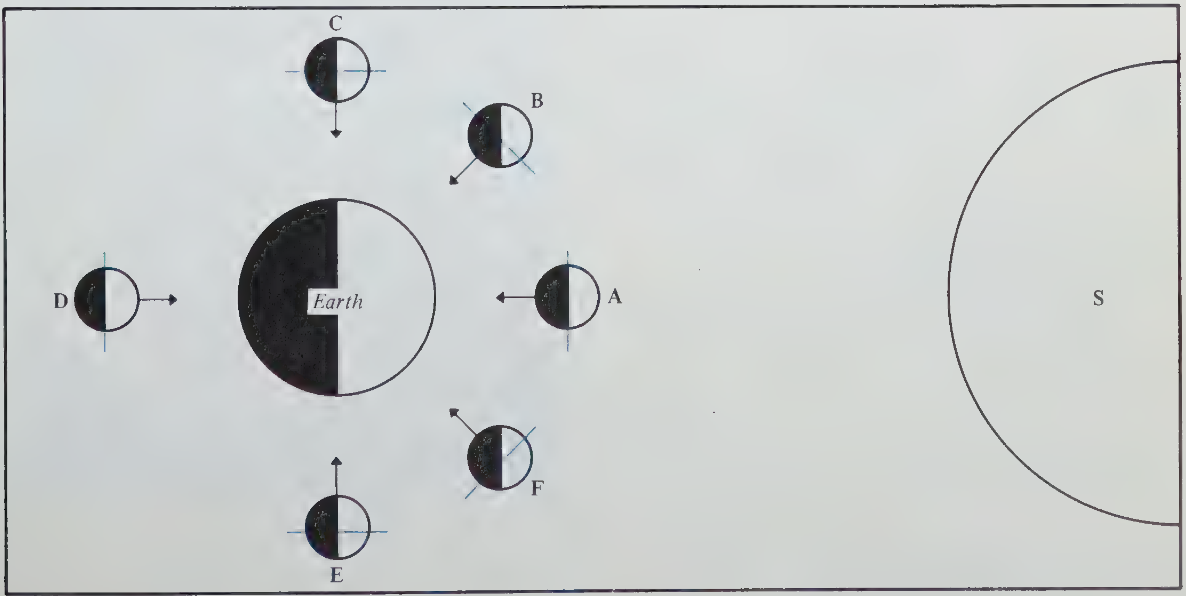
The moon's phases are interesting to watch, but they have no direct effect on the earth except for the tides. When the moon is full or new, it is lined up with the sun and earth. Then the combined gravitational pulls of sun and moon produce very high tides, called "spring tides." When the moon is at its quarter phases, the pulls of the sun and moon are at right angles to each other. The weak tides at those times are called "neap tides."

You might think that if the moon rotates, we should see all sides of it during the course of a month. Figure 1–16 shows that this is not the case. Until man-made probes went around the moon, man had never been able to see the "hidden side" of the moon. The hidden side of the moon is not the same as the dark side. The hidden side is the side that permanently stays turned away from the earth.

The powerful gravitational pull between the earth and the moon is like an invisible cord attached to the lunar surface facing us. The moon's rotation is locked in step with its period of revolution around the earth. The moon both rotates and revolves in 27⅓ days.

Both the hidden and visible sides of the moon are alternately illuminated by sunlight. When the hidden side is lit up, the side facing us is dark (new moon).

FIGURE 1–16
The blue line divides the visible side of the moon from the hidden side. At which point on the diagram is the hidden side of the moon the same as the dark side?



A view of the hidden side is shown in Figure 1–17a. The picture was taken when the moon was near the new phase. Compare it with a familiar view of the earth-facing side (Figure 1–17b). There are no large dark areas on the hidden side. The moon seems to be much more "pock-marked" on its hidden side. Some people thought we might find a great mystery on the hidden side. That has not been the case.

FIGURE 1–17
a. *The hidden side of the moon.*
b. *The earth-facing side of the moon.*
How do the visible and hidden sides of the moon differ?

a.

b.

1–11 Moon Watch

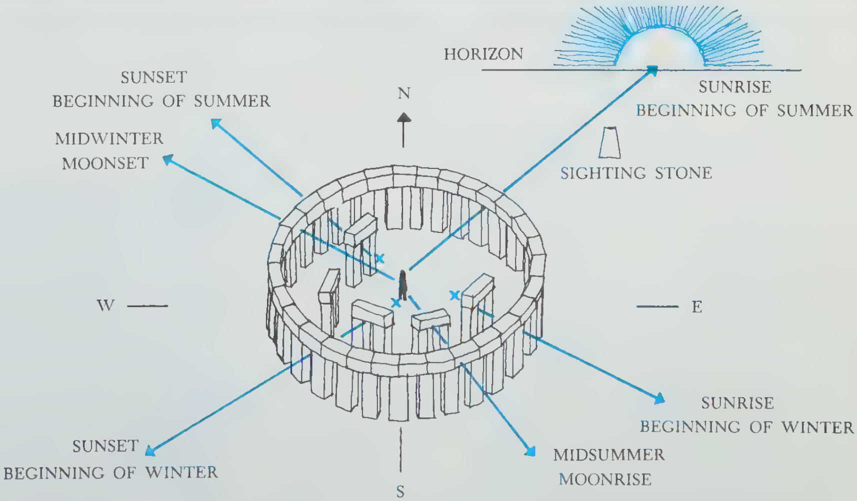
*The phases of the moon were mankind's primary time markers for thousands of years. We owe our word **month** to the moon. It came from the word "moonth," or roughly the time from full moon to full moon. The expression "many moons ago" also refers to lunar cycles. Many ancient temples were erected to the moon. Some served as primitive observatories for ancient "moon watch investigations."* (*See Figure 1–18.*)

PROCEDURE

Observe the moon over a two month period, whenever it is visible. Make the observations as often as you can during this time. Be sure you keep a record of your observations to refer to later. Include the following information on your Moon Watch form:

1. *Date*
2. *Time of each observation*
3. *Is the moon visible?*
4. *The direction of the moon (E, SE, and so on)*

FIGURE 1–18
Stonehenge was built in southern England around 1650 B.C. The men who built this stone observatory used it to keep track of the apparent motions of the sun, moon, and stars. What was the purpose of the sighting stone that was placed outside the ring of rocks?



5. The height of the moon (The horizon is 0°, directly overhead is 90°)
6. The moon's phase
7. Positions of any nearby stars

Moon Watch observations should be made at regular times each day. The best times are on the way to school, going home from school, after dinner, and just after dark. Perhaps you can ask your parents to make a late evening observation for you.

Get into the habit of looking for the moon on your way to and from school. You may have to search carefully for it in the daytime since it is pale compared to the bright blue sky. After two months, you should be able to answer these questions from your notebooks or tables:

1. When you see the moon on your way to school, what phase is it in? What phase is it in on your way home? Does the phase of the moon depend on the time you can see it in the sky?
2. Does the moon rise earlier or later each day?
3. Does the moon move westward or eastward with respect to the stars?
4. How many days elapsed between full moons?
5. How many days elapse before the moon is seen among the same stars again?
6. When the crescent moon is seen in the western part of the sky, is it just before or just after the new moon?
7. Can the crescent moon ever be seen at midnight?
8. Do the points of the crescent point toward or away from the sun?
9. If one evening while sitting in a chair, you see the moon through a window, what time the next night would you have to sit in exactly the same place to see the moon in about the same position in the sky?
10. What time does the first-quarter moon rise?

1–12 The lunar orbit

The distance from the earth to the moon can be easily measured today by radar or by laser beams (Figure 1–19). In both of these cases, radiation is shot toward the moon and reflected back to the earth from the moon's surface. It takes about 2½ seconds for the round trip. The

Figure 1–19
A laser produces light beams of great intensity. It provides the most accurate method of measuring the distance to the moon.

speed of light (laser) and radio waves is exactly the same (300,000 km/sec). The distance to the moon can be calculated from the exact round-trip time.

The moon's distance from the earth varies from a maximum of 406,686 kilometers to a minimum of 356,402. By plotting this daily variation in distance for a whole month, one discovers that the moon's orbit is not quite a circle. It is, instead, an **ellipse**. An ellipse is a closed curve that looks more or less like an egg. You can easily draw one for yourself, as shown in Figure 1–20. The farther apart one places the pins, the more elongated the ellipse becomes. If you bring the pins together in the center, you get a circle. A circle is a kind of ellipse.

A German astronomer, Johannes Kepler, announced in 1609 he had calculated that all planets move in ellipses. Orbiting astronauts also move in ellipses. If you drew the orbit of a planet, the sun would be where one of the pins is in Figure 1–20. Satellites of planets, like our moon, also move in ellipses, with the planet at the pinpoint.

1–13 Eclipses

The orbit of any celestial object lies in a plane. That is, each object is like a marble rolling on a table top (a plane). It moves only in two dimensions.

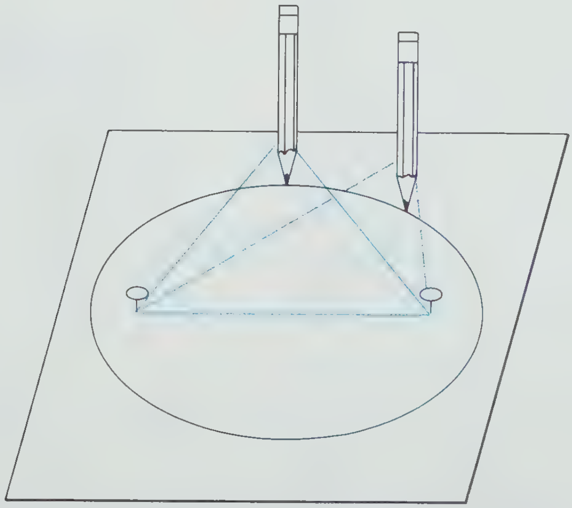


FIGURE 1–20
Drawing an ellipse. If the pencil represents the moon, what represents the earth in this diagram?

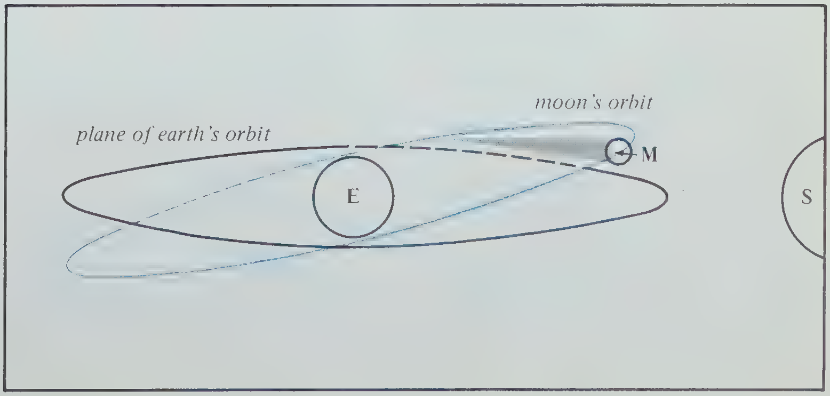


FIGURE 1–21
The plane of the earth's orbit and the moon's. How many times a month are the moon and earth in the same plane?

The orbits of the earth and moon are planes, but the two planes are slightly inclined to each other. The planes cross with an angle of about 5 degrees (Figure 1–21). If both orbits shared the same plane, the moon would pass right in front of the sun every month. We would have an eclipse of the sun at every new moon. Two weeks later, the moon would pass into the shadow of the earth. There would be an eclipse of the moon at every full moon.

Instead, the full moon generally rides above or below the earth's shadow, and no eclipse of the moon occurs. Similarly, only when the moon is near the crossing line of the two planes (called the nodes of the moon's orbit) can it pass directly in front of the sun at new moon. Although invisible at the time, the new moon can be as much as 5 degrees above or below the sun in the sky. (See Figure 1–22.)

At new moon, if the sun, moon, and earth are exactly in line, the moon's shadow will fall on a narrow strip of earth. That part, and only that part, experiences a total eclipse of the sun. A much larger portion of the earth experiences a partial eclipse of the sun. At that time you can look at the image of the sun projected through binoculars or a telescope onto a piece of white paper. A portion of the sun appears "chopped out" by the moon (Figure 1–23).

Total solar eclipses are very dramatic and important scientific events. Astronomers often travel thousands of miles to view one. On such expeditions, excitement runs high as the moment approaches when the moon will completely cover the sun. The skylight just before eclipse is eerie—like a strange twilight. Birds come home to roost, thinking that their bedtime is at hand. Bats often come out of their caves, and an unearthly mood suddenly pervades the surroundings.

Eclipse expeditions have often been sent to primitive places around the world. Sometimes, as the eclipse begins, the people think that the sun is being swallowed by some celestial giant.

Figure 1–23
Why is it important never to look directly at the sun during an eclipse?

Figure 1–22
At new moon, the sun and moon usually "miss" each other by a wide margin. Why is the new moon invisible?

They howl and clamor in their fear and excitement. The ancient Chinese thought that a dragon was swallowing the sun. They beat gongs and made all kinds of noises to frighten it away. In a few minutes, light returns, and the people think they have averted a calamity.

A sequence of photographs of a total solar eclipse is shown in Figure 1–24. It is only during a total eclipse that it becomes dark outdoors. Then the glorious solar **corona,** the huge, thin atmosphere of the sun, shines out for all to see. A good example of a solar corona is shown on page 434.

1–14
Gravity

We live on the bigger, more massive partner of the earth-moon system. Because the earth *is* more massive than its companion, life is possible here and impossible on the moon. Life as we know it requires an atmosphere. The moon's gravitational field cannot keep atmospheric gases from escaping into space. Gravity depends on how massive a body is. Thus, the moon's small gravity (just $\frac{1}{6}$ that of the earth) dooms it to barrenness and inactivity.

The surface of the moon is not constantly changing like the earth's surface. On the earth the rivers wear down the land and carry much of it into the sea. The increasing weight of the ocean floors eventually helps to raise new mountain ranges and land masses.

On the moon, there is no wind or moving water to blow, splash, sweep, gouge, pat, push, and slap the moon's face into new expressions. The face of the moon can be changed by collisions with meteoroids, causing new craters to appear. But these remain nearly unchanged for millions of years. The moon probably has some weak volcanic activity left over from a more youthful stage. This, too, may occasionally change the moon's surface slightly. But all in all, the moon's surface is an unchanging territory compared to the surface of the earth.

Even the earth's gravity is not powerful enough to prevent the escape of hydrogen gas, by far the most abundant chemical element in the universe. Actually this is a fortunate circumstance. If the earth's gravity was much greater conditions on earth would be very different. We would have an atmosphere like Jupiter's, largely composed of hydrogen and some poisonous gases containing hydrogen. Our atmosphere would be so thick and cloudy that we should never be able to see the sun.

Planets like Jupiter and Saturn are so massive that they hold a vast, life-snuffing atmosphere. The reverse is true of the moon and

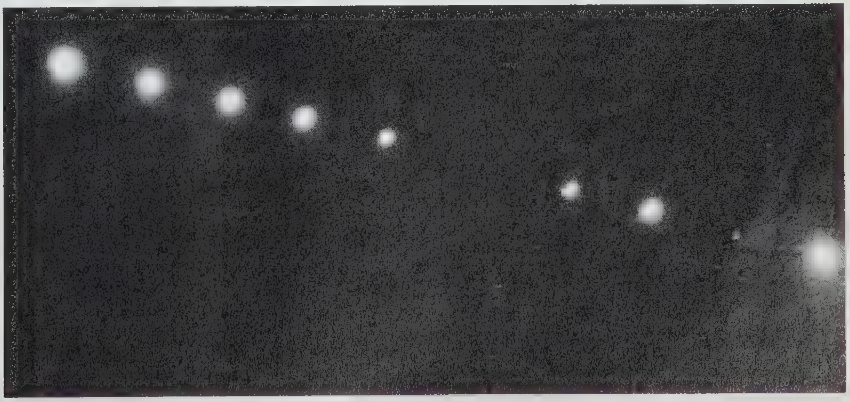


FIGURE 1–24
A total eclipse of the sun.

planets like Mercury and Mars. They are not massive enough to hold a life-supporting atmosphere. We owe our lives to the fact that the earth was born with the right mass and size to give us a transparent, moisture-carrying atmosphere.

Will we always have a life-supporting atmosphere? Slow natural changes are taking place in the chemical content of our atmosphere that could alter the conditions of life on earth. Probably by far the most important changes in the composition of our atmosphere come from man himself. Fumes from automobiles, smoke from factories, and poisonous gases from industrial processes change our atmosphere for the worse.

Thought and Discussion

1. Many people, including news commentators, confuse the hidden side of the moon with the dark side. How would you explain the difference to them?
2. Do you think astronauts on the way to Mars could ever see the full moon?
3. Have you ever seen a total solar eclipse? A partial eclipse? Describe your experience to the rest of the class. What is the main difference in appearance between a total and a partial eclipse? Why do you have a better chance of seeing a partial eclipse of the sun?
4. Why don't we have an eclipse of the sun every month?

Unsolved Problems

You can read this chapter as a series of answers to many famous scientific questions, such as:

> What is the size and shape of the earth? How do the planets move? What causes eclipses? What causes the tides? What is on the hidden side of the moon?

In a way, answering the old questions makes the earth scientist's job harder. The new questions often call for subtler, more complex answers. And often, the new questions combine earth science problems with social and psychological problems. In fact, most of the big questions of earth science are no longer purely scientific. For example:

> What are the precise physical resources of the earth and how shall they be used and distributed? How do man's activities affect the atmosphere and oceans? How will long space flights effect the bodies and minds of astronauts? Should the United States try to send astronauts to other planets?

Chapter Review

Summary

Man did not have to venture into space to discover the earth's motions and dimensions. Rotation could be demonstrated with a Foucault pendulum and revolution by the Doppler effect. Long before space travel, men knew that the earth's tilted axis caused the changing seasons.

Man also discovered many facts about the moon without leaving earth. The moon has an elliptical orbit, it always shows the same side to

earth, and it is the major cause of tides. Man did have to go to the moon to photograph the hidden side and dispell the mystery attached to it.

The Space Age has given us a new view of ourselves. Today we can see our earth-moon system by television relay from outer space or on films brought back by the astronauts. We can see our cosmic situation at a glance—our home on a small atmosphere-carrying planet.

Back on earth it is easy to lose our perspective. We can be fooled into thinking we live on a flat, stationary earth. The view from space tells us directly and quickly that the earth rotates on its axis while it journeys around the sun.

But there are many details about our planet that are best studied right on the surface. That study is the subject of this book.

Questions and Problems

A

1. What is the difference between rotation and revolution?
2. What evidence can you give that the earth rotates?
3. What evidence can you give that the earth is revolving?
4. What factors cause the seasons?
5. If the earth's orbit around the sun and the moon's orbit around the earth were in the same plane, how often would eclipses occur?

B

1. If you observe one particular star for an hour, in what direction will its position change in relation to you?
2. What causes the lag of the seasons?
3. The sun is very much more massive than the moon. Why does the moon have the greater influence in producing tides on earth?
4. How much of the moon's surface is visible at the new moon phase? at full moon?

C

1. How could you use the Doppler effect to prove that Mars is rotating?
2. Is it possible to launch a satellite that would, when in orbit, always be located over the same spot on the earth's surface?
3. Suppose the earth kept the same face toward the moon all the time. Would there be any tides?

Suggested Readings

BOOKS

Hynek, J. Allen, and Apfel, Necia, *Astronomy One*. W. A. Benjamin Company, Menlo Park, California, 1972.

Moore, Patrick, *The Atlas of the Universe*. Rand McNally & Company, New York, 1970.

Reilly, Judith G., and Van der Pyl, Adrian W., *Physical Science: An Interrelated Course*. Addison-Wesley Publishing Company, Inc., Reading, Massachusetts, 1970.

Sagan, Carl and the editors of *Life*, *The Planets*. Time, Inc., New York, 1966.

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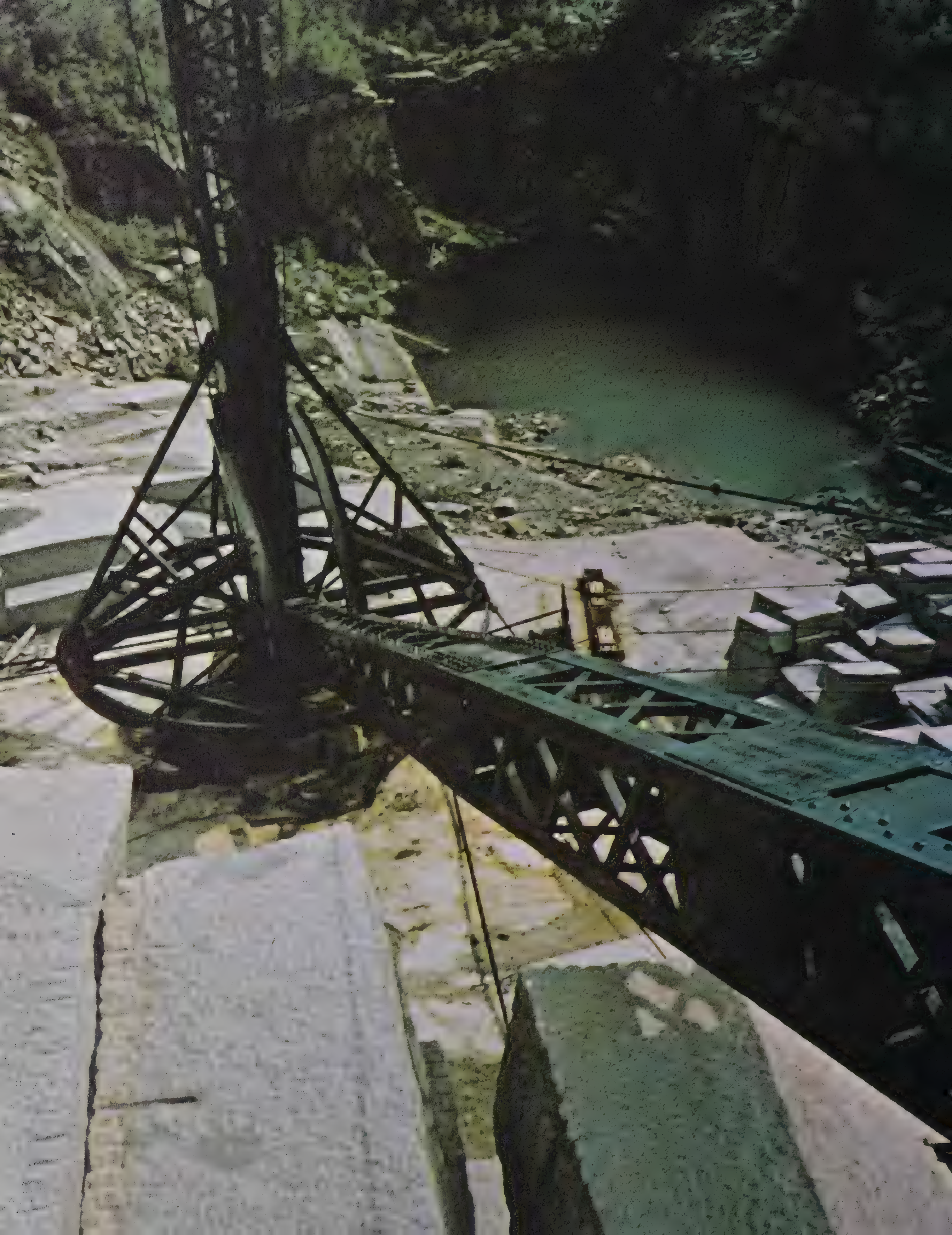
Federer, Charles A., ed., *Sky and Telescope*. Sky Publishing Corporation, Cambridge, Massachusetts.

Weaver, Kenneth F., "Voyage to the Planets." *National Geographic*, August, 1970, p. 147.



2. Earth and Moon Materials

When you go home tonight, make some observations around your neighborhood. How many things can you identify that came from the earth? Where do we get the materials to make lampposts, sidewalks, and houses? What are the steps, foundations, and walls of buildings made of? Where do auto makers get the iron, aluminum, nickel, and chrome that they need?

The world of man-made things is created from our natural resources, things from the earth. We have learned to use these resources and often to shape them into objects of great beauty. But first, the resources must be found. The earth, like a squirrel, has usually hidden her wealth underground.

Most rocks do not contain usefully high concentrations of valuable minerals. Many prospectors, earth scientists, and engineers work around the world trying to discover rich deposits like the iron ore bodies of Minnesota, the coal beds of Pennsylvania, and the oil fields of Texas.

In recent years, there has been great concern about the earth's reserves of natural resources. There isn't an endless supply of anything. Will we eventually run out of some basic materials, or will a greater effort be made to "recycle" them? For example, what happens to an old car? Should it be left on a roadside to disintegrate back into the soil or a stream? Or should it be recycled and the valuable metal used again?

What of the moon? Could it supply us with minerals? Samples of the moon have been brought to earth. Scientists are beginning to learn what the moon is made of. We know the composition of the moon rocks and soil. What we learn about moon materials may also tell us more about earth materials.

Rocks and Minerals

2–1
Comparing earth and moon materials

In a photo of the earth from space you can see the colors of three different kinds of earth materials. Patterns of white clouds swirl above the surface of the earth. Openings in the cloud cover reveal blue patches of ocean, and the land looks brown or red.

We can classify or group the earth materials into three basic types. The word used to describe the rocks in the solid outer crust of the earth is **lithosphere.** (The Greek word *lithos,* means stone.) The water in the oceans, rivers, and icefields is the **hydrosphere.** (*Hydro* is Greek for water.) The air moving in currents around the earth forms the **atmosphere.** (*Atmos* is the Latin word for vapor.)

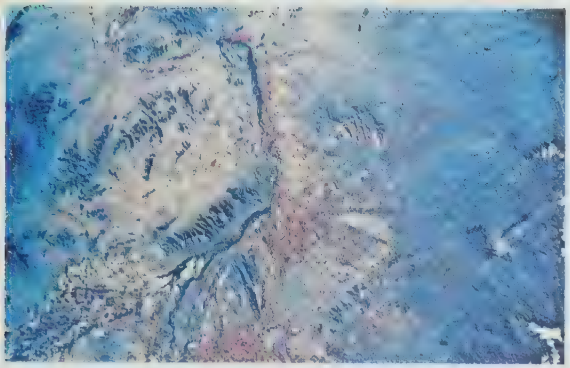
Any place where the lithosphere, hydrosphere, or atmosphere meet is called an **interface.** Try to identify the interfaces in Figure 2–1. Interfaces are not always distinct. The atmosphere may contain both water and solid particles. Rocks and soils contain water and air, while streams and oceans can contain air and solid materials.

Although the moon and earth are a double planet, they are very different. Photographs of the moon show no clouds or water, only rocks in shades of gray and white. Scientists have not found water in the moon rocks brought back by Apollo astronauts. There may be water beneath the surface of the moon, but there is no hydrosphere like earth's. Nor is there an atmosphere. The moon's gravity is not strong enough to hold down oxygen and nitrogen. In one respect, moon and earth are comparable. There is recent evidence that the moon, like the earth, is made of a series of layers.

Figure 2–2 zeroes in on earth materials. You can see different characteristics in each scale of observation. From a satellite or a plane you can see the Superstition Mountains of Arizona, but not what they are made of. The building units of mountains, shown in ever greater detail in Figure 2–2, are *rocks* made of *minerals,* made of *atoms,* made of *subatomic particles.*

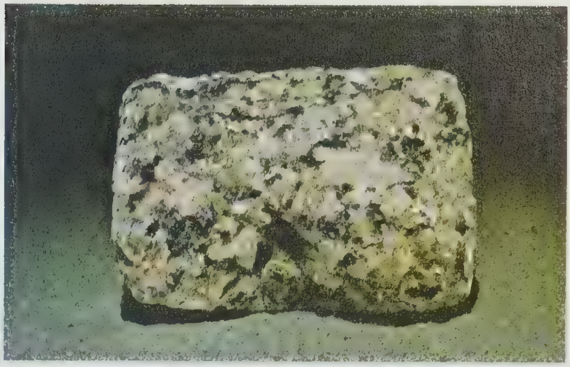
FIGURE 2–1
Earth materials can be solids, liquids, or gases. What interfaces can you see in this picture?

a.

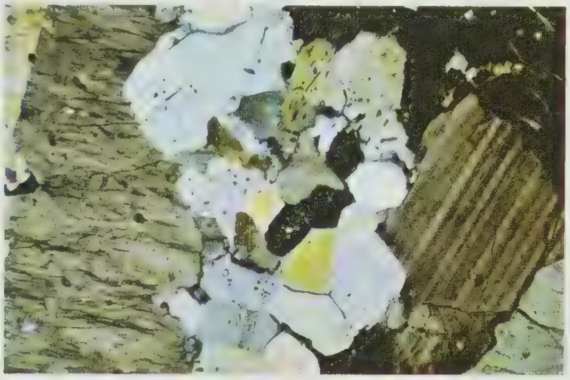


b.

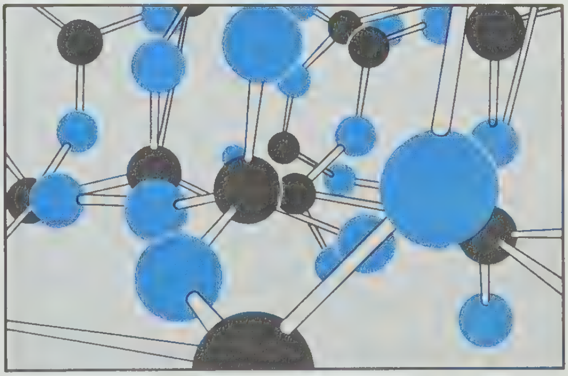
c.



d.



e.



f.

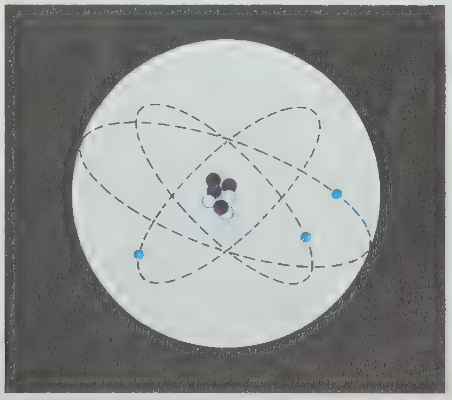


FIGURE 2–2
Focusing on earth materials at different scales:

a. *earth from space*
b. *ground view of the Superstition Mountains*
c. *rock specimen from Superstition Mountains*
d. *photomicrograph of a thin section of rock*
e. *model of the internal stucture of a mineral in the rock*
f. *model of an atom*

2–2
The origins of rocks

There are many kinds of rocks. Did you ever start a rock collection? If you did, you can probably remember wondering how to group your rocks. The first people who were curious about rocks may have grouped them by colors. As earth scientists examined and grouped rocks, they found that color was not the most important property to use in classifying them.

The early study of rocks raised a number of questions. For example, why are there so many kinds of rocks, and how did they form? Earth scientists observed that certain rocks occurred in layers that were similar to the layers of sand and mud in lake bottoms and along the seashore. Other rocks had properties observed in lava from volcanoes. Eventually, these observations led to a classification system for rocks based on the way they probably formed.

It is useful to separate rocks into three principal classes: **igneous, sedimentary,** and **metamorphic.** We will study the processes that form the various classes in later chapters.

Igneous rocks form when molten materials from deep in the earth cool and harden. (See Figure 2–3.) "Igneous" stems from the Latin word *ignis*, meaning fire.

Igneous and other types of rocks on the surface of the earth are weathered. **Weathering** is the chemical and physical breakdown of rock exposed to the air and water. For example, when water freezes in a crack in a rock, it expands causing the rock to break apart. The pieces of weathered rock that collect on the earth's surface are continually moved by water, wind, and ice. This process of moving materials is known as **erosion.** Erosion eventually carries much of the weathered rock to the oceans where it is deposited in layers of sediments.

The sands and other sediments that make up our beaches are pushed out along the bottom of the sea. In time they can be covered by other sediments and can solidify, becoming rock. Rocks formed in this way are called sedimentary rocks. They can form from particles eroded from any type of rock exposed at the earth's surface. Figure 2–4 is a good example of a sedimentary rock.

Metamorphic rocks are formed from other rocks that are heated or strongly squeezed together for long periods of time deep beneath the surface of the earth. The original rocks and their minerals are changed and new forms appear. Sedimentary rocks changing into metamorphic rocks can be compared to blocks of soft clay being pressed and heated into bricks. Metamorphic rocks may also form from igneous rocks. The type of metamorphic rock formed depends on the amount of heat and pressure and on the chemical composition of the original rock. (See Figure 2–5.)

Because the moon has neither an atmosphere nor a hydrosphere, rapid weathering is impossible. However, extremes of heat and cold during lunar days and nights, solar winds, and meteorite impacts do change the moon's surface features. Weathered rock is not washed or blown away. All it can do is slump down the sides of craters. The ravaged face of the moon shows us a record of meteorite impacts since the moon was formed. These impacts cause lunar erosion at an extremely slow rate and on a very small scale compared with our dynamic earth. Thus the moon can be considered a "dead planet."

a.

b.

FIGURE 2–3
a. (*top*) *Surtsey volcano rose above the surface of the Atlantic Ocean near Iceland in 1963.*
b. (*left*) *solidified "ropy" lava*

FIGURE 2–4
(right) What is the most noticeable feature of this sedimentary rock?

FIGURE 2–5
(bottom right) Compare this metamorphic rock with the rock in Figure 2–4.

2–3
Investigating rocks and minerals

You have seen many different kinds of rocks in your life. You could probably list at least a dozen kinds. Have you ever examined rocks carefully? Exactly how do they compare with each other?

Procedure

To find out how rocks are different, take the ones your teacher has set out and describe each one as carefully as you can. Make a separate list of words that describe the characteristics of each rock. Are some terms better than others for identifying rock properties?

In the next part of the investigation you will examine a sample of crushed rock. Use a magnifier and a teasing needle to separate the crushed material into piles of similar particles. (See Figure 2–6.) Now make a list of descriptive terms for each pile you made. Compare this list to the one you made for the rocks. Which was easier to describe? Why?

Figure 2–6

2–4
Investigating mass, volume, and density

Look at the two beakers in Figure 2–7. Each beaker contains a liquid and a solid. In the beaker on the left, the liquid is water and the solid is a piece of granite. The beaker on the right also contains a piece of granite, but the liquid is mercury. What difference between the mercury and the water accounts for what you observe?

Before you can answer this question, you must learn about a property common to all matter: ***density***. The density of a substance can be calculated by dividing its **mass** by its **volume**. The mass of a substance is the amount of matter it contains. The volume of a substance is the amount of space it occupies. Density is commonly expressed in terms of grams (mass) per cubic centimeter (volume).

$$\text{Density} = \frac{\text{Mass (g)}}{\text{Volume (cc)}}$$

This means that you can obtain the density (D) by dividing the mass (M) by the volume (V), as follows:

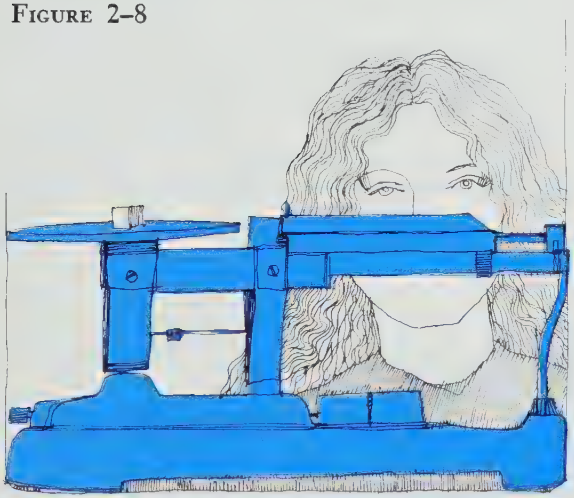
$$D = \frac{M}{V}$$

Suppose that an object has a mass (M) of 100 grams and a volume (V) of 20 cubic centimeters. What is its density (D) in grams per cubic centimeter? The number you calculate is the mass of 1 cubic centimeter of the substance.

FIGURE 2–7

Why does a piece of granite sink to the bottom of the left beaker but float in the liquid in the right beaker?

FIGURE 2–8



PROCEDURE

PART A—DETERMINING SOME DENSITIES Calculate the density of each of the objects given to your group. To do this, you must know both the mass and the volume of the objects. Use a balance to determine the mass, as shown in Figure 2–8. Volume can be determined in many ways. One way is shown in Figure 2–8. Can you think of another? After a class discussion, decide what method or methods you will use. Determine and record the mass and volume of each object. Make a table to help you record and organize your data.

1. What effect does the difference in the shape of a substance have on its density? Explain your answer.
2. What effect does the difference in the amount of the sample have on the density of the modeling clay? Explain your answer.
3. Arrange your materials in order of decreasing density.
4. What is your calculated value for the density of water?

PART B—DETERMINING THE DENSITY OF AN ICE CUBE Now that you are familiar with density, you are ready for another problem. Observe the demonstration by your teacher. Using the materials at your station, determine the approximate density of an ice cube.

1. What is the approximate density of your ice cube?
2. Explain how you obtained this value.
3. Sometimes ice cubes have holes or air spaces in them. Would these spaces affect the density of the ice cube?

2–5 Elements

Some minerals occur in the form of **crystals.** Crystals are solids with regular geometric shapes and smooth flat surfaces called **faces.** The faces show a definite pattern. (See Figure 2–9.) In many cases the crystalline structure is not obvious because the material is made up of a great many very small crystals packed together. Almost all minerals form in geometric shapes because they are made up of smaller parts, so small that you cannot see them.

The mineral, cinnabar, for example, can be separated into two other substances: mercury and sulphur. (See Figure 2–10.) The mercury and sulfur cannot ordinarily be broken down. They are known as **elements.** Cinnabar is called a **compound** because it is made up of elements. Most minerals are compounds, but some such as gold, silver, and diamond contain only one element. Whether they are compounds or elements, they are called minerals if they occur naturally.

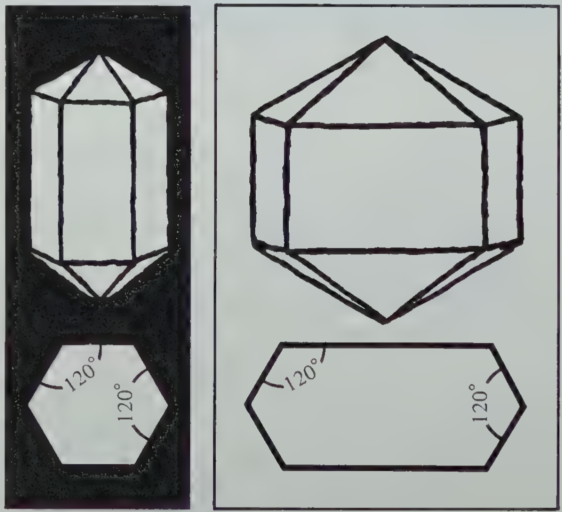
The term "element" has a long history. Over 2,000 years ago the Greek philosopher Empedocles taught that matter consists of the four "elements": earth, air, fire, and water. (See Figure 2–11.) He believed that all materials were made by combining these four elements.

Men had known for a long time that heating a certain soft red rock with charcoal would change it into a much harder gray material called iron. This change was thought to be a rearrangement of the elements of fire, water, earth, and air in the red rock. Why then, reasoned some early experimenters (possibly the Hittites who discovered iron) couldn't the gray metal be changed into shiny yellow gold? Thus was born the "science" of alchemy, the search for a way to change common earth materials into valuable gold. Suppose the discovery had been made. How valuable would gold have been then and now?

Alchemy was practiced for many centuries, partly as a science, partly as a swindle. Although the alchemists never succeeded in making gold, they did make many valuable scientific discoveries. They realized for example that certain substances like iron, mercury, gold, and sulfur could not be further broken down or changed into other elements. Alchemists also concluded that since they were able to extract iron from certain red rocks, the iron must have been present in the composition of the rock.

You are probably aware of many elements, for example, gold, aluminum, copper, and oxygen. You can find a complete list of all the 108 known elements in Appendix C.

FIGURE 2–9
Two crystals of a substance can look different, but the angles between some of the faces are always the same.



a.

b.

c.

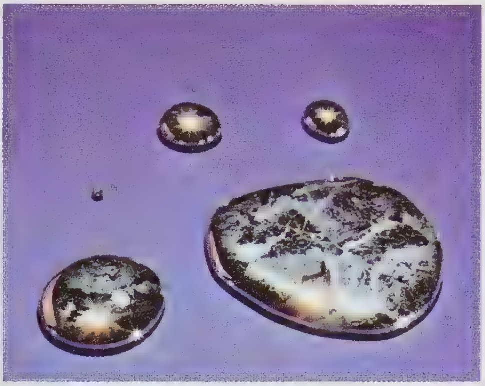


FIGURE 2–10
a. *the compound cinnabar*
b. *the element sulfur*
c. *the element mercury*

FIGURE 2–11
An artist's view of Empedocles' theory of matter. From this chaos of "elements" all the earth materials formed. What evidence could Empedocles have had for his theory?

Because the names of some elements are too long to use easily, a system of chemical symbols is used to identify them. The symbols are a kind of shorthand for the names of the elements. For example, H represents hydrogen, O is oxygen, and Ca stands for calcium. To avoid using the same symbol for elements starting with the same letter, scientists sometimes use the first letters of the Greek or Latin name for the element. For example, the symbol for sodium, Na, comes from the Latin word *natrium* (NAY-tree-uhm).

In a chemical formula, numbers written below a symbol indicate the ratios of atoms in a compound. The chemical formula for lime is CaO, because lime contains one atom of calcium for each atom of oxygen. (Chemists don't bother to write the number one below the chemical symbols.) Lime is made by heating a rock called limestone. The most common mineral in limestone is calcite, $CaCO_3$. What is the ratio of atoms in calcite?

ACTION *List all the elements you know. At room temperature, which elements are solid? Which are liquids or gases?*

Thought and Discussion

1. What is the difference between a rock and a mineral?
2. Why is the moon considered a "dead planet"?
3. What is the difference between an element and a compound?
4. What is the difference between a metamorphic rock, a sedimentary rock, and an igneous rock?

Atoms and Molecules

2–6
Atoms and their parts

You now know that minerals are naturally occurring solids, composed of one or more elements. Are elements the smallest parts into which matter can be broken? If so, what makes the elements different from each other? Do elements account for the tendency of minerals to form crystals? Questions such as these led scientists to a theory explaining even smaller parts of minerals and elements: atoms.

A Greek philosopher named Democritus suggested more than 2,000 years ago that all matter is made up of tiny particles called atoms. His idea was not generally accepted.

The English scientist John Dalton laid the foundation for the modern atomic theory but not until 1808. He proposed the following ideas to explain the differences between elements and to account for the behavior of gases.

1. All substances are composed of small, solid, indestructible particles called atoms.
2. The atoms of a given substance have the same size and shape.
3. The atom is the smallest particle of an element that enters into chemical changes.
4. Compounds are formed by combinations of the atoms of two or more elements.

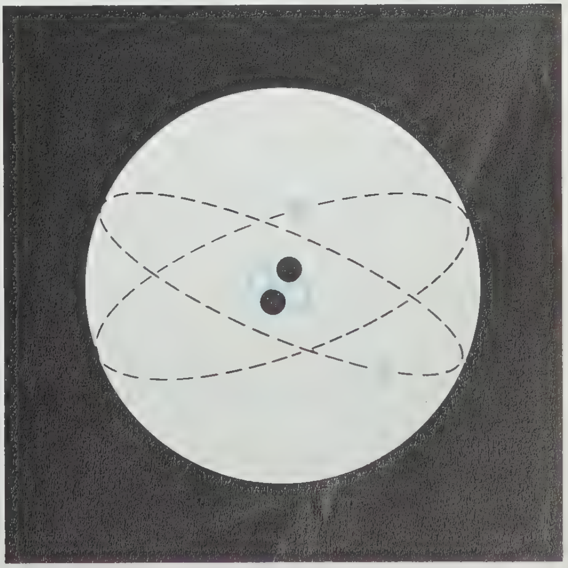
Later scientists discovered that even Dalton's indestructible atoms could be broken down. Today a large number of subatomic particles (smaller than an atom) are known. The main building units of the atom are **electrons, protons,** and **neutrons.** The electron was the first particle to be recognized as a basic part of all atoms. This recognition came with the discovery that electricity consists of a stream of moving electrons. Each electron has one unit of negative (−) electrical charge. Since atoms do not have a negative charge, scientists reasoned that there were also particles with a positive (+) charge. These charges would balance to make the atom electrically neutral. The proton, 1800 times heavier than an electron, was soon discovered. In 1932 the neutron was discovered. It has about the same mass as a proton, but no electrical charge.

Once the main parts of an atom were known, scientists began to form a mental picture or model of the structure of atoms. They found that atoms behave like tiny spheres with a nucleus in the center. The nucleus is made up of protons and neutrons and is surrounded by clouds of orbiting electrons. A model of the simplest atom, the hydrogen atom, is shown in Figure 2–12.

Hydrogen atoms have no neutrons and only one proton and one electron. The slightly more complex helium atoms in Figure 2–13 contain all three particles. Since protons and neutrons are 1800 times heavier than electrons, nearly all of the mass of an atom is concentrated in the nucleus. In an element, all the atoms have the same number of protons in the nucleus. This number partly determines the properties of the different elements.

FIGURE 2–12
A model of a hydrogen atom. Electrons are actually in constant motion and their orbits keep changing.

FIGURE 2–13
A model of a helium atom. How many protons, neutrons, and electrons does it have?



You have already learned that most minerals are made of several substances called compounds. For example, the mineral galena is composed of lead and sulphur; the mineral quartz is composed of silicon and oxygen; and a ruby is made of aluminum and oxygen with a small amount of chromium. Electrical forces hold these atoms together. The atoms are so close to each other that the paths of some of their electrons overlap. These charged particles are "shared" by the atoms and bond them together. The nature of atomic bonds is not easy to understand or explain briefly. The idea of overlapping paths and shared electrons should give you a rough idea of bonding.

All atoms of a particular element may not be exactly the same. They will all have the same number of electrons and protons, but the number of neutrons can vary. For example, if a neutron is added to a hydrogen atom, **deuterium** is formed (Figure 2–14). It behaves chemically like ordinary hydrogen, but it has almost twice as much mass. The atoms of an element that differ only in mass are called **isotopes.** Scientists have discovered that isotopes of many elements occur in nature. Some of the isotopes of uranium, strontium, and thorium, are unstable and are known as **radioactive isotopes.** They "decay" or break down to form other isotopes by giving off subatomic particles and energy. Radioactive isotopes have been used to determine the ages of rocks, to destroy cancer cells, and to make nuclear bombs.

Figure 2–14
A model of a deuterium atom. Deuterium combined with oxygen forms "heavy water." It is used to cool nuclear reactors.

2–7
The unusual water molecule

Water commonly occurs in three different phases: solid, liquid, and gas. A *solid* has a definite volume and a definite shape. Ice is a solid. A *liquid* also has a definite volume but no definite shape. Like the water you drink, it takes the shape of its container. A *gas* has neither a definite shape nor a definite volume. Water vapor will expand to fill any size container.

Just knowing that the water molecule (H_2O) is composed of two parts hydrogen and one part oxygen gives no clue to its unusual properties. It is the special way that the hydrogen and oxygen ions are joined that accounts for water's behavior. Figure 2–15 shows a model of the atoms in the water molecule.

Because the angle between the hydrogen atoms is less than 180°, the hydrogen atoms are essentially bonded to one side of the oxygen atom. Therefore, that end of the molecule has a positive charge and the other end, the oxygen end, has a negative charge (although overall the

molecule has no net charge). Thus, opposite ends of water molecules attract each other. Scientists have calculated that if the molecules were not attracted to one another, water would boil below 0° Celsius rather than at 100° Celsius. (The Celsius temperature scale is described and compared with the Fahrenheit scale in Appendix B. Celsius is abbreviated as C.)

Figure 2–15
A model of a water molecule.

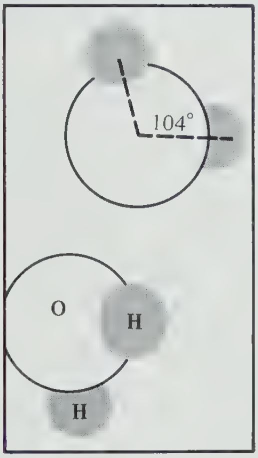
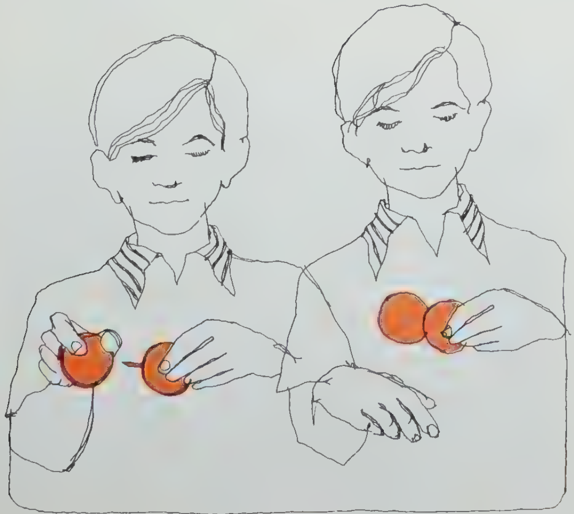


Figure 2–16



Action *You can construct models of how oxygen atoms combine with atoms of other elements. These models are useful even though they do not show how strongly different atoms are bonded to the oxygen. The strength of bonds partly determines physical properties.*

Begin by joining two of the large spheres with connectors as in Figure 2–16. This makes a model of the oxygen molecule (O_2) in the atmosphere. Next, make a water molecule (H_2O) by connecting two small spheres to another of the large spheres so that the centers of the small spheres are about 104 degrees apart.

How could you arrange two nearby water molecules so they will attract each other? Would water behave differently if the oxygen and hydrogen atoms were in a straight line?

The mutual attraction of water molecules is also responsible for another property of water that you have observed: surface tension. You can fill a glass with water, and then add more until the water level is higher than the top of the glass. The strong mutual attraction of the water molecules results in a thin "skin" across the top of the water surface. *Carefully place a clean needle or razor blade on top of a quiet water surface. What happens? Why?*

One of water's most important properties is its ability to dissolve **salts**, such as sodium chloride (NaCl). Again, the positive and negative charges on water molecules are responsible. Salts are combinations of positive and negative **ions**. An ion is an atom that does not have the same number of electrons as protons. It has a net electrical charge. If there are extra electrons, the charge is negative (Cl^- for example).

If it has less electrons than protons, the charge is positive (Na^+). Ions with opposite charges attract each other. Ions with similar charges repel each other. Because they are electrically unbalanced, positive and negative ions can combine to form stable, neutral compounds.

When salt is placed in water, the ions are loosened from their fixed positions. Ions on the surface of the salt are surrounded by clusters of water molecules. The positive ends (the hydrogen atoms) point toward negative chloride ions. The negative ends (the oxygen atoms) point toward positive sodium ions. If enough water molecules do this, the ions break free. The salt begins to dissolve.

When water freezes to ice, the molecules arrange themselves in the pattern shown in Figure 2–18. (Do you think that ice is a mineral?) There is more space between the water molecules in ice than in liquid water. Water therefore expands as it freezes. Is ice more or less dense than liquid water?

2–8 Many minerals need special conditions to form.

Some minerals form only at high temperatures. If the same atoms combine at low temperatures, they form a different mineral with a different structure. Other minerals, such as diamond, form only under high pressure. Still others are the product of special chemical conditions. Two forms of FeS_2 are shown in Figure 2–19. Pyrite and marcasite are combinations of iron and sulfur formed under different chemical conditions.

The high value of precious stones is due to their hardness, scarcity, and beautiful colors. Most gems are scarce because they were formed under very special conditions of temperature and pressure. These conditions were not duplicated very often in nature.

The diamond (Figure 2–20a) is perhaps the best known and most valued of the gemstones.

Figure 2–17
Clusters of water molecules around a sodium ion and a chloride ion. Which is the sodium?

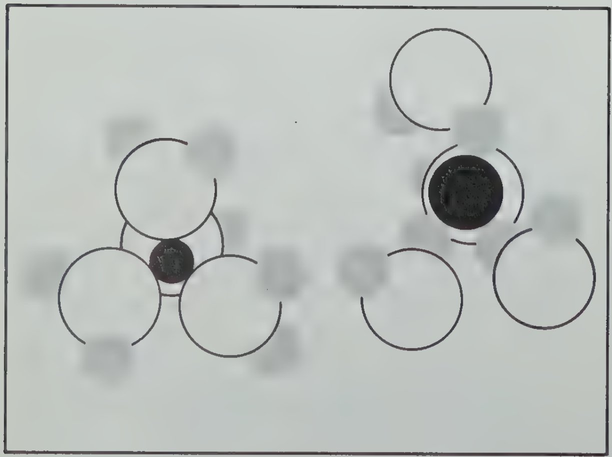
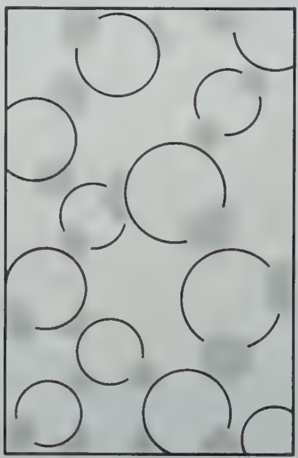
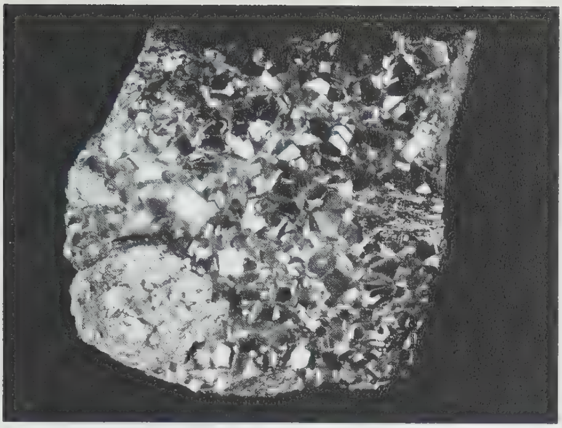


Figure 2–18
When water freezes to ice, the molecules arrange themselves in a pattern.



a.



b.

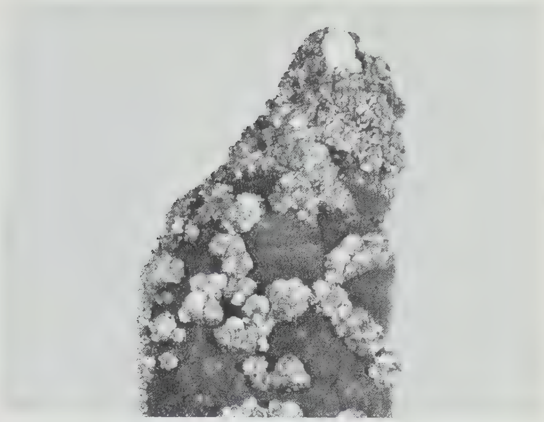


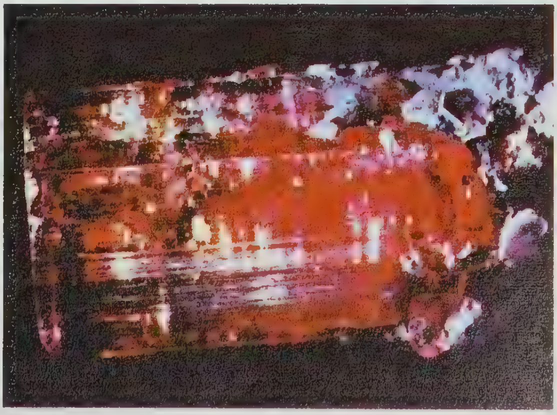
FIGURE 2–19
The same chemical compound, iron sulfide (FeS_2) occurs in two mineral forms: a. *pyrite,* b. *marcasite (the light-colored clusters).*

a.

FIGURE 2–20
a. *A diamond crystal from South Africa, still embedded in igneous rock.*
b. *Ruby crystals fom Tanzania embedded in green rock.*
c. *A tourmaline crystal from Brazil found in pegmatite.*

b.

c.



It has a unique crystal structure that makes it harder than any other mineral and also gives it a brilliant luster. Most diamonds are found in Kimberlite. This is a volcanic rock pushed up through the crust from deep within the earth. Concentrations of Kimberlite and diamonds are found in India, Brazil, and South Africa.

In 1955 after many years of trying, scientists succeeded in producing artificial diamonds. Before then all efforts to make carbon crystallize into the diamond form resulted in the formation of graphite. Success in forming diamonds was achieved by using extremely high pressures. Knowing this, what can you conclude about past conditions in the part of the crust where a diamond crystal is found?

Minerals that form only at certain temperatures and pressures are important for the geologist who is working out the history of the earth. He may learn from laboratory studies that a mineral forms only at temperatures above 300°C no matter what the pressure. When he finds this mineral in a rock layer, he can infer that the temperature there was at least 300°C when the rock was formed.

2–9 Mineral properties and atomic structure

Different arrangements of carbon atoms produce diamond and graphite. Both minerals are composed only of carbon. Yet diamond is the hardest natural substance known, and graphite is so soft and flaky that it is used as a lubricant. By using x rays, we can examine the

Figure 2–21
How does the arrangement of carbon atoms in a diamond account for its extreme hardness?

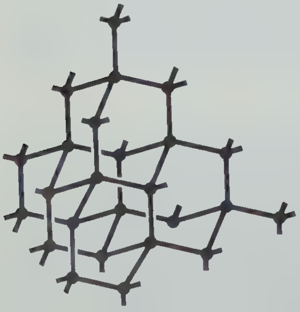


Figure 2–22
Why does the structure of graphite make this form of carbon soft and flaky?

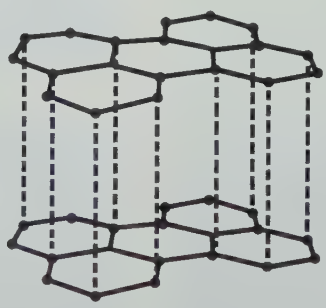
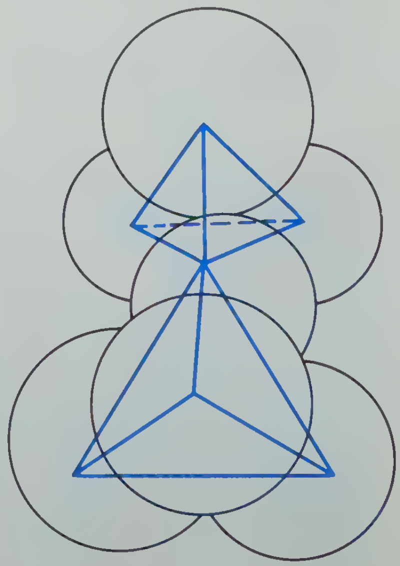


Figure 2–23
Silicon-oxygen tetrahedrons can join together by sharing oxygen atoms.



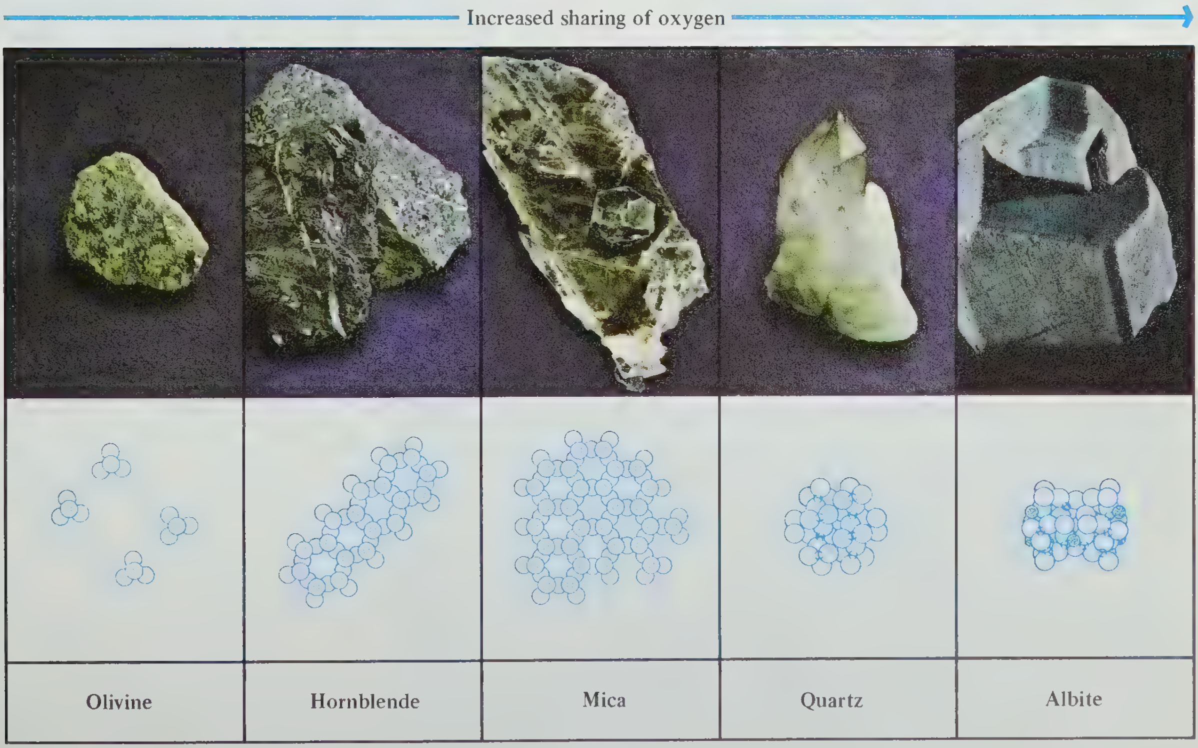
arrangement of the atoms in diamond and graphite crystals. These arrangements are shown in Figures 2–21 and 2–22. The x rays are reflected from rows of atoms in the crystals. We infer that the different crystal structures cause the varying physical properties of these two forms of carbon.

Silicon combines with oxygen and other common elements to form the **silicate minerals.** Because these minerals are by far the most abundant type of material in the earth's crust, they have been called the "rock-forming minerals." They illustrate the relation between atomic structure and the physical characteristics of minerals.

In all of the silicate minerals, silicon and oxygen are joined in a tetrahedral (four-sided) arrangement, so that four oxygen atoms surround each silicon atom. The chemical formula is SiO_4. These silicon-oxygen tetrahedrons can occur singly, or they can join together by sharing oxygen atoms, as illustrated in Figure 2–23. The different arrangements of tetrahedrons determine the properties of the five common, rock-forming silicate minerals pictured in Figure 2–24.

The relation between the atomic arrangements of minerals and their physical properties is not always as clear as in these examples. Other factors, such as the elements in a mineral and the way atoms are bonded, also affect the properties.

FIGURE 2–24
In these common silicate minerals, the tetrahedrons occur in different patterns.



Action *Take four large spheres (oxygen atoms) and one small sphere (silicon atoms) and put them together as compactly as possible. All of the oxygen atoms should be an equal distance from the silicon. This is a model of a silicon-oxygen tetrahedron—the basic pattern of oxygen and silicon in the silicate minerals of the earth's crust.*

Build several other tetrahedrons in the same way. Try to put two of them together. What must you change in order to join two tetrahedrons so that they share an oxygen atom as shown in Figure 2–23? Silicon atoms in adjacent tetrahedrons may share only one oxygen atom with any other silicon.

Try to build a straight chain of the silicate tetrahedrons. What would be the silicon-oxygen ratio in this chain? These ratios are expressed in the nearest whole numbers. What element do you think makes up the greatest percentage of the earth's crust?

Thought and Discussion

1. Why isn't it useful to describe a crystalline solid like sodium chloride in terms of molecules?
2. How are minerals useful in reconstructing past earth conditions?
3. Air, water, and minerals all contain atoms. Why, then, are these materials so different?
4. Are the properties of minerals mainly the result of their chemical composition or are other factors more important?
5. Can you predict the arrangement of atoms in a mineral specimen by looking at its overall shape?

The Abundance of the Elements

2–10
The composition of earth and moon rocks

You already know that you need oxygen to live and that water is composed mostly of oxygen. However, it may come as a surprise to you to learn that oxygen, which we normally think of as a gas, is the major element of the earth's solid crust. The **crust** is the outermost layer of the earth. It averages 20 miles (33 kilometers) in thickness. Oxygen makes up almost 94 per cent of the volume of the crust. This is because oxygen atoms are much larger than the atoms of other common elements like silicon or aluminum. You can think of the earth's crust as a framework of large oxygen atoms with the smaller atoms of other elements filling in the spaces between.

The average composition of the earth's crust is shown in Figure 2–25. The values given here are based on chemical analyses of rocks from all over the world. Seemingly common elements like carbon, copper, nickel, lead, and sulfur do not appear in Figure 2–25 because they each make up less than one per cent of the crust. Eight elements listed in the table account for

98.5 per cent of the weight of the crust. All other elements make up only 1.5 per cent. Copper, for example, makes up only 0.0045 per cent, lead only 0.00015 per cent, and gold only 0.0000007 per cent of the average composition of the earth's crust.

The earth's crust is in a constant state of change. As a result, its composition is highly variable. Change may increase or decrease local concentrations of some elements. Fortunately, there are areas where elements like copper may make up 2 to 20 per cent of the rock. (See Figure 2–26.)

The composition of the moon's crust also varies from place to place. Samples collected by Apollo 14 astronauts were different from those brought back by Apollo 12 astronauts. Without many samples from all parts of the moon, scientists cannot describe the average composition of the moon's crust. But they can make some tentative comparison between earth and moon rocks. Moon rocks have a much higher titanium, chromium, iron, and zirconium content. But nickel, sodium, and potassium are less abundant. Carbon and nitrogen are common on earth but very scarce on the moon.

FIGURE 2–25
The Average Chemical Composition of the Earth's Crust

ELEMENT	SYMBOL	PERCENTAGE IN CRUST	
		By Weight	*By Volume*
OXYGEN	O	46.6	93.8
SILICON	Si	27.7	0.9
ALUMINUM	Al	8.1	0.5
IRON	Fe	5.0	0.4
CALCIUM	Ca	3.6	1.0
SODIUM	Na	2.8	1.3
POTASSIUM	K	2.6	1.8
MAGNESIUM	Mg	2.1	0.3
ALL OTHER ELEMENTS	—	1.5	—
TOTAL		100.0	100.0

FIGURE 2–26
Blasts at Kennecott's Utah copper mine break loose more than 375,000 tons of material at one time.

"A moment was all that was necessary to strike off his head, and probably a hundred years will not be sufficient to produce another like it." Joseph Louis Lagrange, astronomer and mathematician (1736–1813), mourning Antoine Lavoisier, who was guillotined during the French Revolution.

In 1772, the French chemist Antoine Lavoisier (1743–1794) looked at fire and tried to discover explanations for it. Fire was almost as mysterious to 18th century man as to primitive man. No one understood burning. One scientist, George Stahl, believed that objects that could burn were rich in a substance called phlogiston (floh-JISS-tun), and this phlogiston was lost during burning. Stahl said that wood had phlogiston, but the ashes from wood did not. The phlogiston theory was popular with scientists, although no one ever saw or measured the mysterious substance.

Lavoisier began his experiments by burning a variety of substances, like phosphorus and sulfur, and making observations. He liked to make accurate measurements. He weighed each substance he burned, before and after burning. When he studied his measurements, he discovered that instead of losing something to the air, the burned substance must have gained something. It weighed more after burning than before.

Joseph Priestly had just discovered that objects burn more easily in a special gas, which was later called oxygen. Lavoisier, using this information, reasoned that air had oxygen in it. The secret to burning was that burning takes place when a substance combines with the oxygen in the air. It was a great idea. It excited curious people everywhere. But, almost as important as the idea was the accuracy of measuring that Lavoisier insisted on. He showed the scientific world the value of careful observations. It meant a new, more exact way of finding out about the world.

2–11
The common elements in the atmosphere and hydrosphere

By weight, water is 88.9 per cent oxygen and 11.1 per cent hydrogen. The oxygen atom is by far the most abundant component of the hydrosphere. If you have ever tasted sea water or the water of salty lakes, you know the hydrosphere contains other elements. Almost every element found in the crust is present in sea water in very small amounts. You will learn why these ions

are in the sea when you study the water cycle in the next unit.

Moon rocks are extraordinarily free of water in any form. The superdry pieces of lunar crust absorbed large amounts of water when they were exposed to the earth's moist air.

The composition of air was analyzed only 200 years ago by Antoine Lavoisier (La-vwah-ZYAY). In the 1770's Lavoisier performed a brilliant series of experiments with air. In one experiment he heated a bottle of mercury in a fixed amount of air in a large bell jar. For 12 days he heated the mercury at just under its boiling point. At first, red particles formed on the mercury. The particles stopped forming before 12 days were up. Lavoisier calculated that the original 800 cubic centimeters of air in the bell jar had been reduced to between 670 and 685 cubic centimeters.

He reasoned that the 115 to 130 cubic centimeters of air had somehow been taken up by the mercury to form the red particles. He found that the gas remaining in the bell jar was less dense than ordinary air. It put out the flame of a candle and quickly suffocated a mouse. Lavoisier called this gas "azote." You know it as nitrogen.

He then collected the red mercuric particles and heated them to a high temperature. They gave off between 115 and 130 cubic centimeters of gas, the amount previously removed from the air. This gas made candles flame more brightly and did not suffocate a mouse. He called it "air eminently respirable, pure or vital." It was later named oxygen. The red particles were mercuric oxide.

From many chemical analyses, we now know that air is a more uniform mixture than the lithosphere. Two gases, oxygen and nitrogen, account for 99 per cent of the gases in the lower atmosphere. (See Figure 2–27.) Carbon dioxide is a very small, but important part of air. Carbon dioxide absorbs much of the heat that is radiated toward space from the earth's surface. Furthermore, all plants depend on carbon dioxide to carry on photosynthesis. Nitrogen compounds are also vital to plant life. Certain bacteria can take nitrogen from the atmosphere and turn it into usable nitrates for plants.

The earth's atmosphere is never completely dry. Water may make up as much as 3 per cent of the atmosphere under very humid conditions. Because of this wide variation from almost 0 per cent to about 3 per cent, water is not entered in Figure 2–27. You see some of this water as clouds, but most of it you cannot see for it is in vapor form. The importance of this small amount of water in the atmosphere is the subject of future chapters.

FIGURE 2–27
Composition of the Atmosphere at Sea Level, Excluding Water

NAME	CHEMICAL COMPOSITION	PERCENTAGE BY VOLUME
NITROGEN	N_2	78.1
OXYGEN	O_2	20.9
ARGON	Ar	0.9
CARBON DIOXIDE	CO_2	0.03
OTHER MATERIALS		0.07
TOTAL		100.00

Thought and Discussion

1. The atmosphere and the hydrosphere have remarkably uniform compositions compared to the lithosphere of the earth. Why is this so?
2. If the crust contains such small amounts of elements like copper and lead, how can man obtain these useful materials?
3. Can you suggest reasons why the moon has no atmosphere and hydrosphere?
3. Look up the composition of the sun. How does the earth differ from the sun in composition?

Unsolved Problems

Although the average composition of the atmosphere, hydrosphere, and lithosphere is reasonably well known today, scientists are uncertain how these spheres have changed in composition with time. Were the seas as deep and extensive a billion years ago as they are today? Did they contain the same quantity of dissolved materials then as now? Was the atmosphere composed of the same gases in the geologic past? If not, when did the present atmosphere develop?

Much remains to be learned about conditions under which minerals form. Scientists use minerals as guides to past conditions on earth and moon. To do this they must determine experimentally the conditions necessary for their formation. This work is complicated because many variables are involved. A particular mineral may form only at high temperatures under one set of conditions, but in the presence of certain other minerals it may form at lower temperatures. To use minerals to interpret past conditions, scientists must discover all of the variables that can affect mineral formation.

Chapter Review

Summary

In this chapter you looked at earth materials from several vantage points—far out in space, close up with the unaided eye, and even closer with a magnifying glass in the laboratory. You also learned how moon materials differ from earth materials.

Early scientists, in an effort to bring order to their studies, classified various earth materials. Their initial observations led them to investigate the origin of rocks. Now scientists are classifying moon materials in an attempt to better understand their origin.

The invisible basic parts of all matter are the atoms and molecules. Most of the different earth and moon materials are made up of only a few elements. The way atoms of these elements are combined determines the characteristics of a substance. The nature of the water molecule determines both the characteristics of water and the composition of the hydrosphere. Oxygen is the most abundant element in the earth's and moon's crust and in the waters of the earth as well. It is also an important part of the air. Finally, the silicate minerals are the most common minerals on both earth and moon, and the feldspars are the most abundant silicates.

Questions and Problems

A

1. What is the difference between an element and a compound?
2. What is an ion?
3. What subatomic particles form the nucleus of an atom?
4. Is ice more or less dense than water?
5. How does the abundance of metals in the earth's crust compare with the abundance of oxygen?
6. How do earth and moon rocks differ?
7. Why are moon rocks unaffected by chemical weathering?

B

1. What is the difference between an atom and an ion?
2. What keeps atoms together in a compound?
3. How was the practice of alchemy important to the development of modern science?
4. Why do minerals appear in the form of crystals?
5. What did Lavoisier learn about air?
6. Sketch the arrangement of protons, neutrons, and electrons in helium.
7. If water is composed of two parts of hydrogen and only one part of oxygen, why does oxygen make up most of the mass of the hydrosphere?
8. What are some of the qualities of gemstones that make them so valuable?

C

1. John Dalton proposed that all substances are composed of small, solid, indestructible particles called atoms. Are atoms still considered to be small, solid, and indestructible?
2. How does salt (NaCl) dissolve in water?
3. What difference in structure accounts for the fact that mica easily comes apart in flakes whereas quartz breaks irregularly?
4. Look at Figure 2–25. Which atom has the larger volume, the Fe atom or the Na atom?

Suggested Readings

Books

Ernst, W. G., *Earth Materials.* Prentice-Hall, Inc., Englewood Cliffs, N.J., 1969.

Grunwald, Ernest, and Johnson, Russell H., *Atoms, Molecules and Chemical Change,* 2nd ed. Prentice-Hall, Inc., Englewood Cliffs, N.J., 1965.

Leet, L. Don, and Judson, Sheldon, *Physical Geology.* Prentice-Hall, Inc., Englewood Cliffs, N.J., 1971.

Levinson, A. A., and Taylor, S. Ross, *Moon Rocks and Minerals.* Pergammon Press, Elmsford, N.Y., 1970.

Pearl, Richard M., *How to Know the Minerals and Rocks.* McGraw-Hill Book Company, New York, 1955.

Pough, Frederick II, *A Field Guide to Rocks and Minerals.* Houghton Mifflin Company, Boston, 1960.

Skinner, B. J., *Earth Resources.* Prentice-Hall, Inc., Englewood Cliffs, N.J., 1969.

Periodicals

Germer, Lester H., "The Structure of Crystal Surfaces." *Scientific American,* March, 1965.

Mason, Brian, "The Lunar Rocks." *Scientific American,* October, 1971.

3. The Changing Earth

Most of us have been surprised by the appearance of the earth from nearby space, especially by the great areas of white clouds that hide most of the surface most of the time. Familiar land shapes are hard to find. Can you see North America in the picture?

The view from space keeps changing. Much of the cloud cover is made of great spiral whorls. Even in a photo these whorls seem to be rotating. In the tropics the clouds move from east to west across the surface of the earth. In the middle latitudes the cloud cover—whorls and irregular masses—moves from west to east. The earth is rotating in the same direction, but the clouds move faster than the earth below. Our simple observations reveal only a small part of the total changes in the atmosphere. You can think of others. All these movements and changes in the atmosphere require a continuous and abundant source of energy.

The surface of the earth itself is mostly water. A casual observer of the oceans would not see changes comparable to those in the atmosphere. The most familiar movements of the oceans are waves and tides. Waves are the effects of wind rather than changes of the water itself. Tides are an example of regular change within the oceans, and at some places the tides rise and fall 17 meters twice a day. However, the tides have little effect on the oceans as masses of water. Closer observation of the oceans reveals that they do have a complex system of movement and circulation. For example, currents carry Brazil nuts to the coast of Scotland, and young eels are moved from a place near Bermuda all the way to Europe. The oceans' circu-

lation is spectacular in its magnitude and complexity but less obvious and dramatic than that in the atmosphere.

The "solid" earth is also constantly changing. Active volcanoes, earthquakes, and the relentless flow of sediment-laden water to the sea are common knowledge. The slow uplift or lowering of broad land areas are less well known. Systematic investigations of the earth reveal that it has been changing continuously for about four billion years.

Suppose we had a time-lapse movie of North America, with one frame taken every 100,000 years over the past four billion years. It would take about 28 minutes to view. In this movie the continent would seem alive. Continental areas would grow. The shapes of land and sea would be constantly and rapidly changing. You would see long, narrow, shallow seas lying on the eastern and western borders of North America. Rivers flowing into these seas would deposit sand, silt, and clay on the sea floor, layer upon layer. At times the seas would spread across the interior of the continent, submerging half or more of the total area. At times mountain ranges with active volcanoes would emerge from the long narrow seaways.

It is possible that in the early part of the film North America would be joined to Europe as part of a single continent. During the last four minutes of the film, this continent would appear to divide like an amoeba, and North America would move away to its present position. Man would not appear on the earth until the last ten frames of the film: less than half a second of the 28 minute show.

Energy and Change

3–1
Motions of earth materials

The introduction to this chapter mentions some of the basic motions of the changing earth. To understand these motions, we must observe and describe them accurately, and try to understand the energy and the forces that cause them.

ACTION *Produce a photograph, drawing, or description of something in our environment that is changing. This can be a personal or group observation or something you find in a newspaper or magazine. What is the nature of the change? When did it start? How long did it or will it continue? What will be the final result? What causes the change?*

Can you think of something in our environment that never changes? If you can, bring to class a picture, drawing, or description of it.

What forces clouds to move across the face of the earth? Wind you say. Well, what causes the wind? What causes cloud whorls to rotate one way in the Northern Hemisphere and the opposite way in the Southern Hemisphere? What forces the oceans to circulate? Why does water run downhill in streams? What forces molten lava to rise to the surface of the earth? What makes the earth's crust break and snap to produce earthquakes? We are not going to answer all these questions in this chapter. By the time you have finished the course, however,

you should have discovered at least tentative answers to all of them.

Two investigations should start here. You and your classmates will then have the benefit of data you collected on weather and earthquakes when you study these subjects in later chapters.

Some motions of earth materials, such as those in the atmosphere, occur in changing patterns and may be observed anywhere. Other motions, such as those which produce earthquakes, occur in special areas. For most of us, the study of earthquakes depends on reported observations by others.

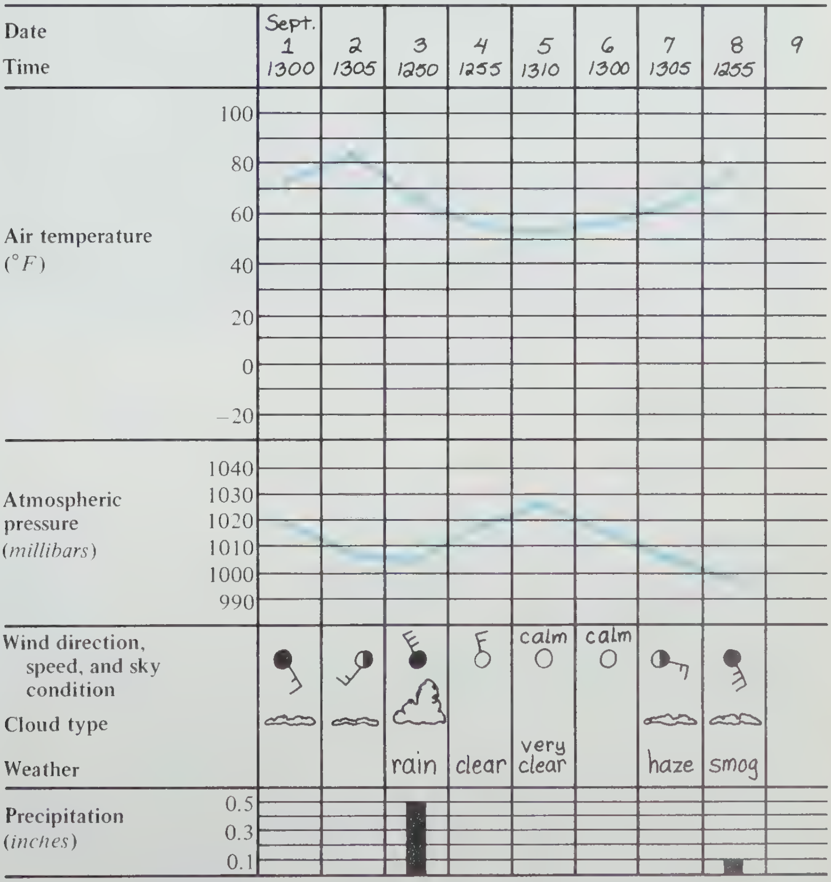
3–2 Investigating patterns of change—Weather Watch

Weather is the condition of the atmosphere at any one time and place. To discover what weather patterns exist in your region, you will have to collect information for a long time.

Procedure

The class should observe and measure the weather for the next two and one-half months. Figure 3–1 is one possible way to organize your data.

Figure 3–1
A sample Weather Watch chart.



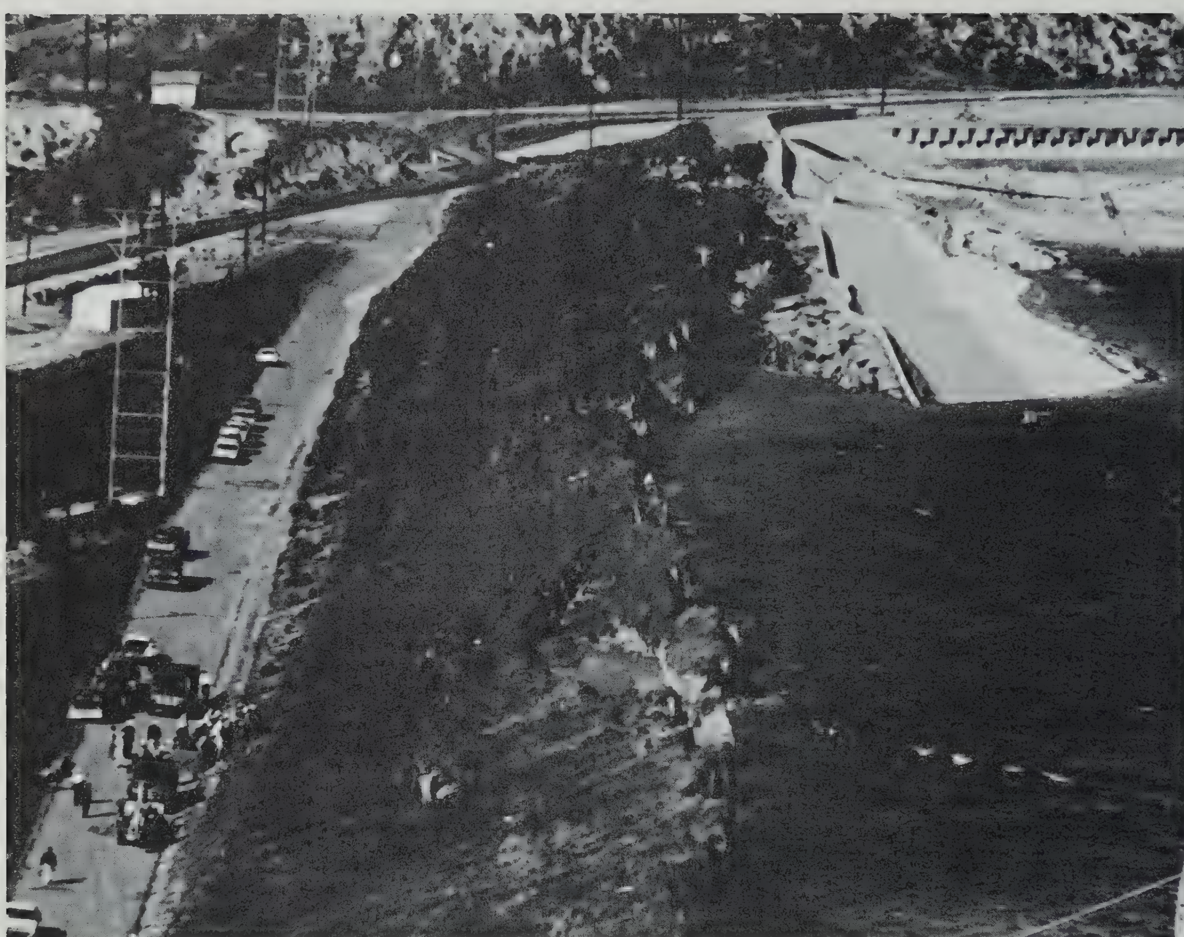


FIGURE 3–2
One spectacular effect of the 1971 Los Angeles earthquake.

FIGURE 3–3

During this time you will keep track of changes in the atmosphere from one day to the next. Use a wall chart to record these changes and see if you can discover any patterns to them. Your observations and records will involve time patterns (in the form of a graph) and space patterns (in the form of a map). See Appendix B for the factors to measure.

Discuss with your teacher how the chart can be constructed so that your observations and measurements will contribute most to the discovery of patterns. By the time you are studying Chapter 5, you may be ready to make some of your own weather predictions.

3–3
Investigating patterns of change—Earthquake Watch

In February 1971 the ground shook under Los Angeles, the most heavily populated county in America. The first upheaval collapsed hospitals, tossed around bridges and slabs of highway concrete, and tore up sewers, water pipes and electric cables. (See Figure 3–2.) In the next few days there were hundreds of minor tremors and 12 major aftershocks. Sixty-two persons died under collapsing beams and rubble. Many more would have died except that the earthquake took place early in the morning, before highways and streets were crowded.

Scientists estimate that as many as 1,000 to 5,000 measurable earthquakes take place around the world every day! Do earthquakes occur everywhere? How often do major quakes occur? Only long-term observations will give you the answers to these questions. You will begin such observations here in the Earthquake Watch.

Procedure

*You will use the data from sensitive detecting instruments called **seismographs**. Seismographs detect the almost continuous trembling of the earth at many different points on the globe. Analysis of the data from three or more seismographs can pinpoint the time and location of an earthquake. It also indicates their depth and magnitude. Perhaps you can discover patterns in earthquake locations and frequency. The information needed for this investigation comes from the National Oceanic and Atmospheric Administration (NOAA).*

*The geographic location of an earthquake on the earth's surface is not the same as its point of origin. The actual place from which an earthquake originates is called the **focus**. It is beneath the surface. The geographic point on the earth's surface directly above the focus is called the **epicenter**. Epicenter locations are given in latitude and longitude. The focus is given as shallow, intermediate, or deep.*

Use map pins to plot the position of the epicenter, as shown in Figure 3–3. Pins of different colors should be used for shallow, intermediate, and deep earthquakes.

3–4
Energy

You are familiar with energy although you may not be able to define the word precisely. Don't look it up in the dictionary but think about your own ideas of energy. Most of us think of energy as our ability to get things done. We

sometimes feel we are "full of energy" and are ready to do a lot of work. Or, we may complain of not having the energy to do anything. This popular idea of energy is something like the scientific concept shown in Figure 3–4.

Heat energy is important in many earth changes, and it is familiar to all of us. We get heat energy from fuels such as wood, oil, and uranium. Food is a fuel, also. Each of these fuels can be said to release energy by burning.

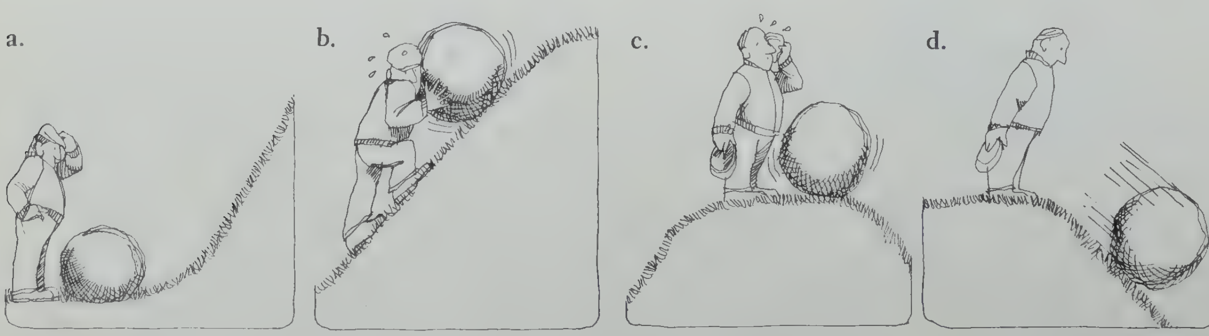
ACTION *Consider two familiar sources of energy: gasoline and electricity. Both are commonly used in engines to do many kinds of work. An engine changes one kind of energy into another, more useful kind. For example, a car engine converts chemical energy into the mechanical energy that turns the wheels.*

Try to trace the energy in gasoline and electricity back to their original sources. Gasoline of course comes from petroleum. Where did petroleum come from? What was the source of the energy locked in the petroleum?

Assume that your electricity comes from a hydroelectric generating plant. Trace the energy back to its original source. Assume instead that your electricity comes from a steam generating plant that burns coal. Again trace the energy to its original source.

Heat can be transferred in three ways, as illustrated in Figure 3–5. In all three instances, heat moves from material at higher temperature to material at lower temperature. Heating by **conduction** involves actual contact. For example, this is what happens when warm air heats cool air. The faster moving molecules in the warm air batter the slowly moving molecules of the cooler air into faster motion. Another way to say the same thing is that the

FIGURE 3–4
a. *An energy system at rest. The man has stored chemical energy in his muscles. It is* ***potential energy.***
b. *Chemical energy is being converted to work. As the rock moves up the hill, it gains potential energy.*
c. *The potential energy of the rock now equals the work done to push it up the hill against the force of gravity.*
d. *When the rock rolls down the hill, its potential energy is converted to* ***kinetic energy.***



higher energy molecules transfer energy to the lower energy molecules.

Heating by **radiation** is also illustrated in Figure 3–5. As atoms and molecules vibrate, they send out waves that travel through space. All objects, even icebergs, send out some radiation. (The iceberg doesn't warm you because you radiate more heat than it does.) Heat rays are called **infrared rays**. Water is partially transparent to light but absorbs infrared rays. Can you recall from swimming in a lake or in the ocean which type of energy penetrates farther into the water, heat or light?

One effect of **convection** is shown in Figure 3–6. Convection involves the actual movement of heated substances. When air next to the earth's surface is heated (by conduction mostly) it expands. The warm air is less dense than the cooler air surrounding it. The denser, cooler air sinks under the influence of gravity and forces the heated air to rise. The effect is commonly described by the phrase "warm air rises." The motions are called **convection currents**.

Gravity is one driving force behind convection currents. The other is the heating element, such as the warm ground. Gravity actually tends to smooth out temperature differences, because the cold air is drawn down to the warm land or water where it can be warmed.

Convection also occurs in liquids, such as

FIGURE 3–5
a. *The simplest method of heat transfer is by direct contact, or* **conduction.**
b. *The girl is being warmed by* **radiation.** *Invisible infrared rays are given off by the fire.*
c. *Warm expanding air rises from the floor register to thaw out an ice skater. This warm updraft is a* **convection current.**

FIGURE 3–6
Different surfaces heat up the air at different rates. Why doesn't the glider follow a straight path?

lakes or oceans. (See Figure 3–7.) It even appears that convection can occur over very long periods of time in materials that you think of as being solid, such as pitch or the rock material beneath the crust of the earth.

3–5 Investigating flow and change in energy

You cannot see energy, but you can observe and analyze the flow of energy and its change from one form to another. You will see one method in this investigation. Perhaps you will be able to think of other ways yourself.

Procedure

PART A *Use the equipment shown in Figure 3–8. Turn on the light and record the temperatures each minute for 10 minutes. Turn the light off, remove it without disturbing the cans, and record the temperatures each minute for 10 more minutes. Graph the temperature change in each can. Then, answer these questions.*

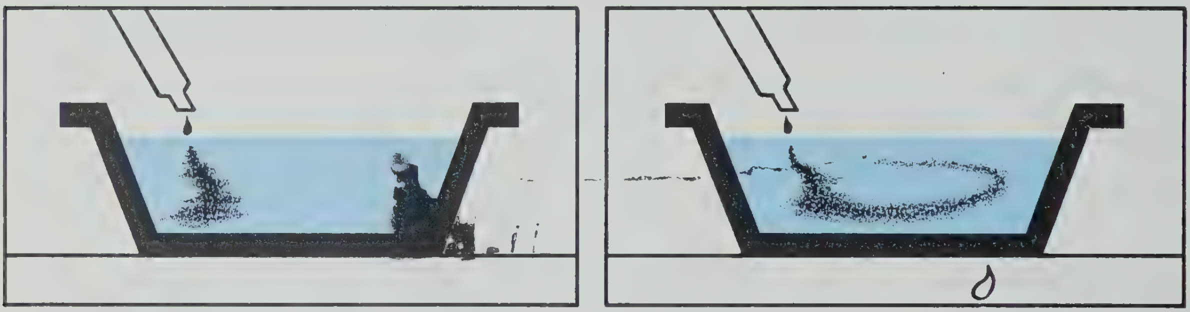
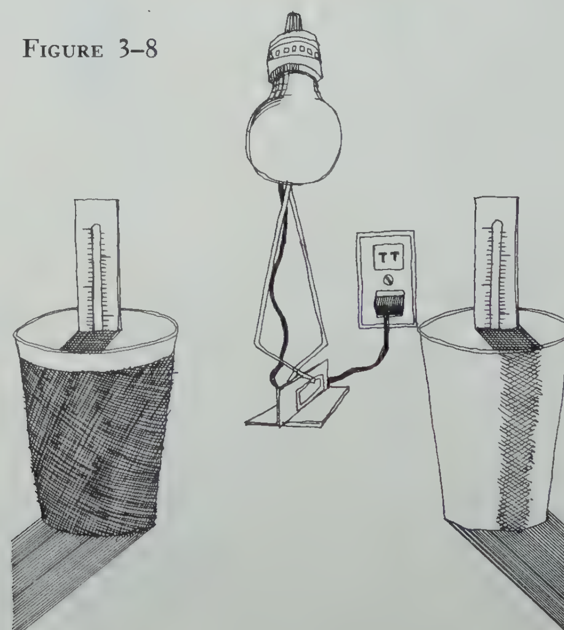


FIGURE 3–7
Heating one end of a tank of water produces convection. Is movement away from or toward the heat source?

FIGURE 3–8



1. *Which can heats faster?*
2. *Which can cools faster?*
3. *Which can absorbs energy better? What is your evidence?*
4. *Which can loses energy faster? How do you know?*
5. *How was the energy transferred in this investigation?*
6. *List and describe the forms of energy you observed.*

PART B *Start the investigation by putting boiling water (100°C) in one container and water at room temperature (approximately 25°C) in the other. Figure 3–9 shows the setup. These containers are insulated to reduce heat loss. Record the temperature reading of each thermometer at four-minute intervals for 20 minutes. Graph your results for both containers on the same graph.*

1. *In which direction does the energy flow? What is your evidence?*
2. *Does energy loss equal energy gain? Explain why.*
3. *Describe the kinds of energy flow you observed in this investigation.*
4. *What could you do to make the final temperature readings in Part B higher?*

3–6
The earth's sources of energy

For every 30 meters (about 100 feet) you go down into a mine, the temperature of the earth increases about 1°C. In a deep hole drilled in west Texas, the temperature was 178°C at a depth of about 8 kilometers. It is believed, though, that the temperature does not continue to increase at this rate all the way to the center of the earth, 6,400 kilometers down. If the temperature did increase at the above rate, what would be the temperature at the center of the earth? Recent theoretical studies suggest temperatures of 4,000°C or less at the center. How does your calculated figure compare with the recent estimate? What do you conclude from this?

You know from Investigation 3–5 that the heat inside the earth cannot come from the cooler surface. Where does it come from then? One theory is that the earth's interior was hot when the earth formed, and that heat has been flowing outward ever since. About 1900 it was found that the earth has a second source of internal heat. The radioactive decay of unstable atoms in the earth's rocks provides a continuing supply of thermal energy.

FIGURE 3–9

During **radioactive decay**, atoms of one element change into atoms of another element. (See Figure 3–10.) The mass at the end of these nuclear reactions is smaller than the mass at the beginning. The lost mass has been transformed into energy according to Einstein's famous equation, $E = mc^2$. In this equation E represents energy, m stands for the amount of mass converted to energy, and c is the speed of light. The speed of light is a very large number: 3×10^{10} centimeters per second. Squaring the speed gives 9×10^{20}. It is not hard to see from

FIGURE 3–10
When a uranium nucleus and a neutron collide, the uranium can split. Barium, krypton, and high energy gamma rays are created. What might happen to the two neutrons that are also released?

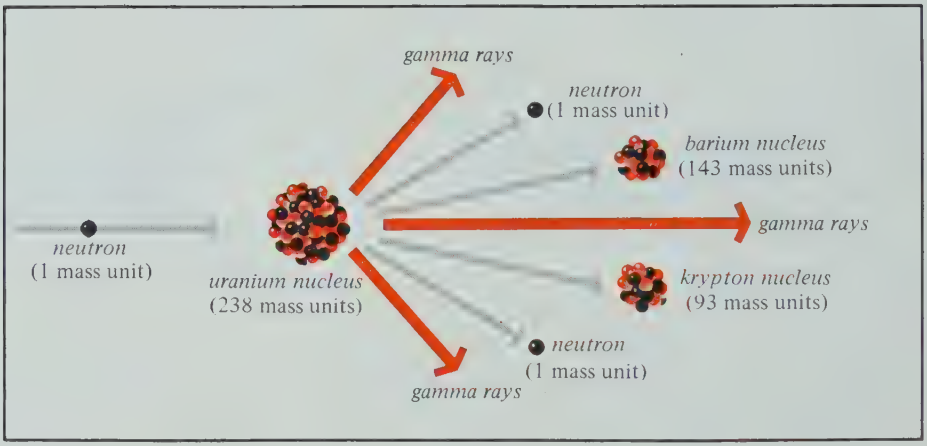
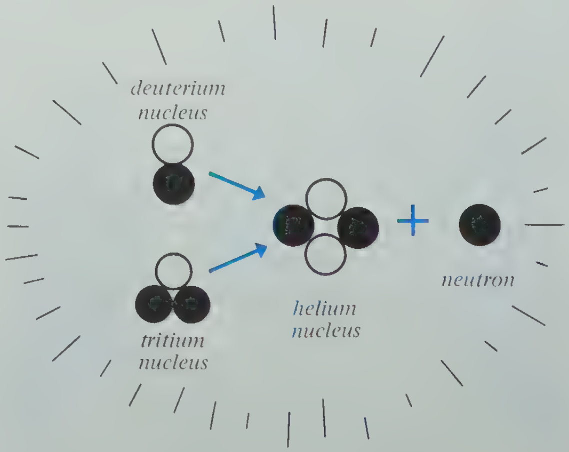


FIGURE 3–11
Deuterium and tritium are two isotopes of hydrogen. When their nuclei unite, more energy is produced per gram of material than in any other reaction in the universe. Fusion only takes place at temperatures above 180,000,000° F.



the equation that even a very small amount of mass will produce a tremendous amount of energy.

Action *Get a cloud chamber containing a piece of radioactive earth material. Watch for evidence that particles are shooting out from the material.*

The flow of heat from the earth's interior is small compared to the amount of radiant energy arriving from the sun. When the sun is overhead, 25,000 times as much energy falls on the earth's surface as flows from the earth's interior. Therefore, the earth's surface temperature, and changes in the hydrosphere and atmosphere, are controlled by solar energy. We could think of the atmosphere and oceans as two great engines powered by heat from the sun.

Our planet receives only a small part of the sun's total energy output. About one two-billionth (5×10^{-10}) of the light and heat pouring out from the sun falls on the earth. But this contributes nearly all the energy supply at the earth's surface. The sun warms the earth as a bonfire warms a mosquito flying around it 30 meters away. The mosquito gets only a small portion of the bonfire's energy, just as the earth receives only a very small part of the sun's total radiant energy.

Nuclear reactions are the only acceptable explanation for the fantastic output of energy from the sun. Analysis of sunlight shows that the sun's surface layers consist of 70 per cent hydrogen and 25 per cent helium. When hydrogen is transformed into helium, a small amount of mass is lost, about 0.7 per cent. (See Figure 3–11.) This mass becomes solar energy.

About 265 million metric tons of matter are changed into energy each minute. (One metric ton = 2205 lb = 10^6g) The sun is something like a controlled hydrogen bomb explosion. Even with this great energy output, it is estimated the sun can burn for another 60 billion years before it runs out of fuel!

Thought and Discussion

1. On a hot day we can observe a "shimmering" effect that extends upward above pavement or soil. These are popularly called "heat waves." What produces the shimmering effect?
2. What happens to the enormous amount of the sun's radiant energy that does not strike the earth?
3. What are the various sources of energy received by the earth's surface?

Earth Forces

3–7
Forces and motion

Forces cause motion. Any kind of motion in any material requires an applied force. Early in the eighteenth century Sir Isaac Newton worked out the relations between force and motion. His results are known as Newton's Laws of Motion.

Newton's first law states simply that a motionless object will remain motionless until a force is applied. Also, a moving object will keep moving in the same direction and at the same speed until a force is applied to it. (See Figure 3–12.) This "stubbornness" of objects (their tendency to keep doing what they have been doing) is called **inertia**. Suppose you are going to push a heavy object, such as a car, on a level surface. It will take a lot of force to get it moving because of the car's inertia. Once it is moving, it will take less force to keep it moving at constant speed. In this instance, the object will slow down and stop if you quit pushing because of friction. However, if you wish to control the slowing down, you will have to apply a braking force.

The second law states that any change in motion is proportional to the force applied and occurs in the same direction that the force acts. For example, to double the acceleration of an object, double the force. If you want to change the direction of the object, another force must be applied in the direction you want it to move. The pine tree in Figure 3–13 has been shaped by a prevailing wind.

The third law states that for every action there is an equal and opposite reaction. The car pushes against you as you push against it. If your feet slip, you are the object that moves. The thrust of rocket engines can either lift the rocket or push the earth away, depending on which (the rocket or the earth) has greater inertia. So far the earth has won these push wars, and the rockets have moved.

3–8 Gravity

Gravity is responsible for most of the natural motions we see every day. Gravity causes rain drops to fall and water to run downhill and seep into the earth. It causes objects denser than the atmosphere to fall toward the earth's surface, boulders to roll, and sleds to slide downhill. When you jump from a high place, you never have to worry which way you are going to go, but only about landing. Why do you think steps are rarely more than 20 centimeters (8 inches) high?

Gravity is the force of attraction that the earth has for any object within, upon, or near it. Gravity holds the molecules of the air so firmly that three fourths of the total mass of the atmosphere is within 10 kilometers of the earth's surface. Gravity provides the basis for defining words such as *vertical* and *horizontal*. Can you define these words in terms of the gravitational attraction of the earth?

ACTION *What is the shape of the ocean surface? From the Gulf of Siam, just south of Bangkok, to the Panama Canal is almost half way around the earth along the 10° North parallel of latitude. One degree of longitude along this parallel has a length of approximately 110 kilometers.*

Draw a semicircle with a radius of 12 centimeters. With the open side of the semicircle down, label the left end of the line Bangkok and the right end Panama. This line represents

FIGURE 3–12
a. *Why does this rock remain perched in a precarious position?*
b. *Space vehicles cannot travel in straight paths. The gravitational attraction of other bodies in space pulls them off course. Rockets must be fired to make course corrections.*

a.

b.

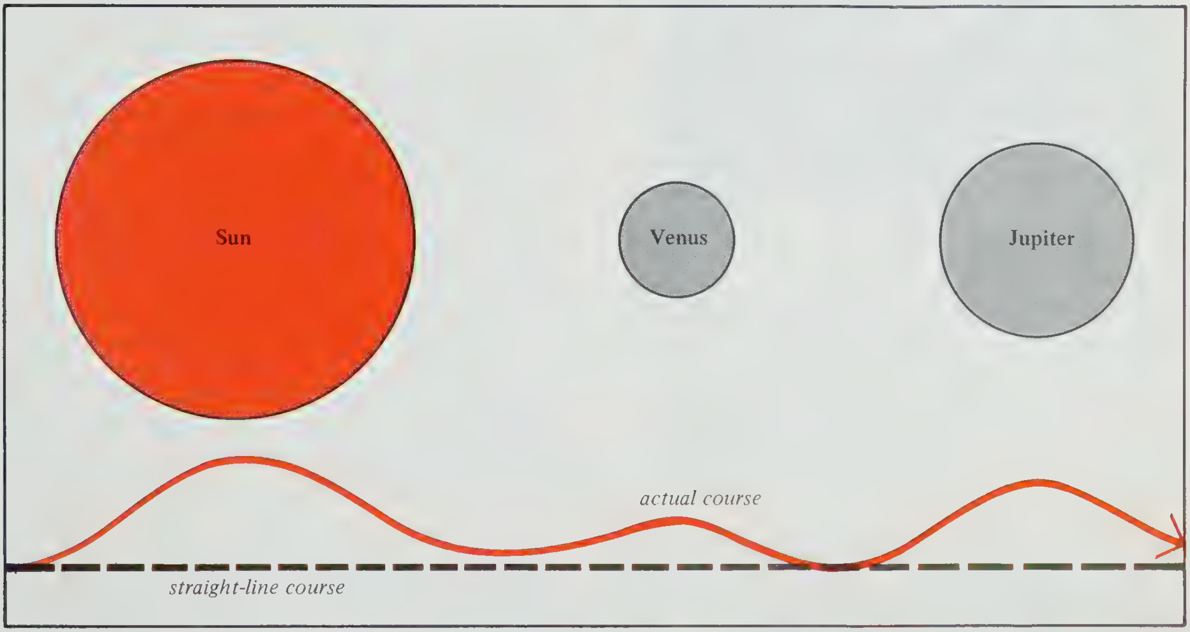
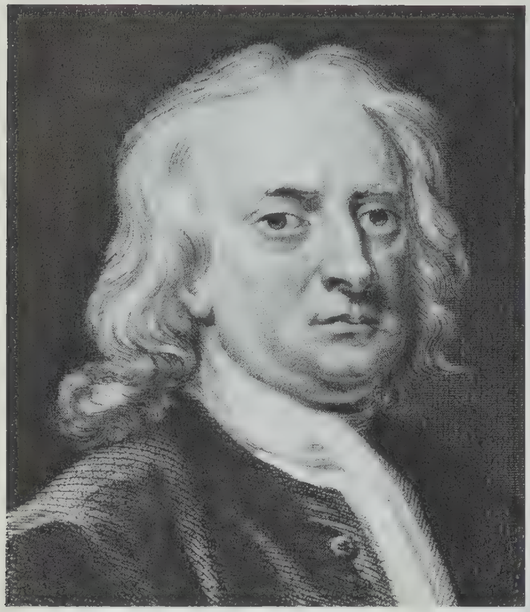


FIGURE 3–13
A growing tree is a moving object. A prevailing wind is a force. This is an example of Newton's second law.

SIR ISAAC NEWTON



It is impossible to contain Newton's life (1642–1727) and work in a small space. He invented an important branch of mathematics, formulated the laws of motion of objects on earth and in the heavens, stated the law of universal gravitation, invented the reflecting telescope, and explained the spectrum, among other things—before he was 30!

Listing achievements may make them seem mechanical, almost easy. First he did this, then he did that. Often though, the hard thing about discovering a new truth is being daring enough to live without the comfortable old explanations. Really new ideas are likely to be frightening.

Until late in the sixteenth century, many Europeans thought the planets were attached to great, rotating glass balls. Without them, it seemed, the planets would not move in regular orbits. They would just drift around in space. Other people believed that space was tightly packed with invisible matter. This matter formed great whirlpools that carried the planets around like pieces of straw. We can see from both theories that men felt some *thing* had to hold up the planets.

Newton emptied the heavens of glass balls and whirlpools. He replaced them with a vacuum and an equation. It linked the vast orbits of the planets with the short paths of falling objects on earth.

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the surface of the Pacific Ocean. Is the sea surface level? Would you describe the line as convex upward, or convex downward? The length of the line represents $180° \times 110$ km = 19,800 km. What is the scale (how many kilometers does a centimeter represent)?

Can you draw another line to represent the bottom of the ocean? The average depth of the ocean along this line is approximately 5 kilometers. The greatest depth (near the western end) is just over 10 kilometers. Use the scale determined above.

The earth's force of gravity is part of a pervasive force known as universal gravitation. There is evidence that gravitational attraction is characteristic of *all matter,* whether deep

within the earth or in distant galaxies. The existence of this universal force and its properties was first demonstrated by Newton early in the eighteenth century. His conclusions are best described by a simple mathematical equation:

$$F = \frac{GM_1M_2}{d^2}$$

F = force
G = gravitational constant
M_1 = mass of one object
M_2 = mass of second object
d^2 = square of the distance between M_1 and M_2

Even though we have been discussing the earth's gravitational force, the equation reminds us that the force of gravity is one of mutual attraction. It depends on two objects.

It is important to understand what relationships this equation expresses. The right side $\frac{GM_1M_2}{d^2}$ is obviously a fraction. What happens to the value of the fraction if the numerator alone increases? What happens to its value if the denominator alone increases? (G is a constant, so its value remains the same.) Will the force increase or decrease if the distance between the two objects becomes larger? What if the distance doubles: will the force be half as much? Will F increase or decrease if one of the masses decreases? What will be the change in F if one mass is reduced by one half? Does it make any difference which mass is reduced?

The force of the earth pulling on a mass of one kilogram is about 9.8 newtons. The force on a person with a mass of 50 kilograms is 50 times as great (50×9.8 newtons = 490 newtons). This is a good place to recall that mass and weight are different. A 50 kilogram person would have the same mass on the moon as on the earth, but not the same weight. The mass of the moon is about one-sixth of the earth's mass. What would be the weight of a 50 kilogram person there?

If the force of gravity is 9.8 newtons, and a falling object has a mass of one kilogram, the downward acceleration can be calculated by another equation developed by Newton:

$$F = m \times a$$
$$(\text{Force} = \text{mass} \times \text{acceleration})$$

In our example the equation becomes:

$$a = \frac{9.8 \text{ newtons}}{1 \text{ kilogram}} = 9.8 \text{ meters / second / second}$$

This acceleration is known as the *acceleration of gravity*. Note: if the mass of the object is doubled, its weight will double, but the acceleration will not change. (Now that you have read that statement do you believe it? Can you explain what it means?)

3–9
Investigating the behavior of a falling object

In this investigation you will examine different kinds of motion and rates of change in motion. Then you will observe the way objects behave as they fall freely. By determining the behavior of a falling object, you will be able to understand certain characteristics of the gravitational field.

PROCEDURE

PART A—DETERMINING RATES OF MOTION *Set up the equipment as shown in Figure 3–14.*

Pull the tape through the timer at a steady rate. Next, pull it through starting slowly and speeding-up during the pull. Then pull the tape through at an irregular rate.

Cut each tape at the dots (Figure 3–14) and paste the pieces of tape down in correct order. The result will be a graph of the rate at which the tape was pulled through the timer.

PART B—BEHAVIOR OF A FALLING OBJECT *Feed the tape through the timer and attach a weight to the end of the tape. Drop the weight off the end of the table.*

Make a graph of the rate at which the weight falls. Compare this graph with your graphs from Part A.

1. *What force pulled the tape through the timer in Part A? In Part B?*
2. *Which of your graphs in Part A closely resembles your graph in Part B?*
3. *How does your Part B graph compare with the Part B graphs of other groups?*
4. *Does the behavior of the falling object in Part B change in different parts of the room?*

The speed of an object is the distance it moves in a certain time. If you measure the distance in centimeters and use one second as the length of time, the speed will be in centimeters per second.

5. *If the time that elapsed between the dots on the tape is one hundredth of a second, what is the speed of the tape in centimeters per second in your steady-rate graph?*

FIGURE 3–14

3–10 Measuring the earth's gravity

Earth scientists use instruments similar to spring scales to measure gravity. (See Figure 3–15.) The springs are arranged so that a very small change in gravity can be detected. Modern gravity meters are lightweight, portable, and very sensitive. Changes in gravity as small as 0.0000001 meters per second^2 can be detected. Such tiny variations provide useful data for earth scientists who investigate the earth's crust by interpreting slight differences in the intensity of the gravity field. The **field** is simply the region where the force can be measured.

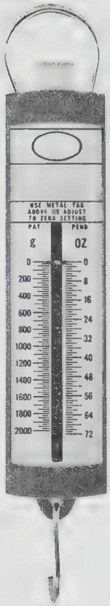
You can see in Figure 3–16 how the force of gravity decreases toward the center of the area above a salt dome. The zero value on the

Figure 3–15

a. *A simple spring scale directly measures the pull of gravity.*

b. *Geophysicists use gravity meters to detect differences in gravitational attraction at the earth's surface.*

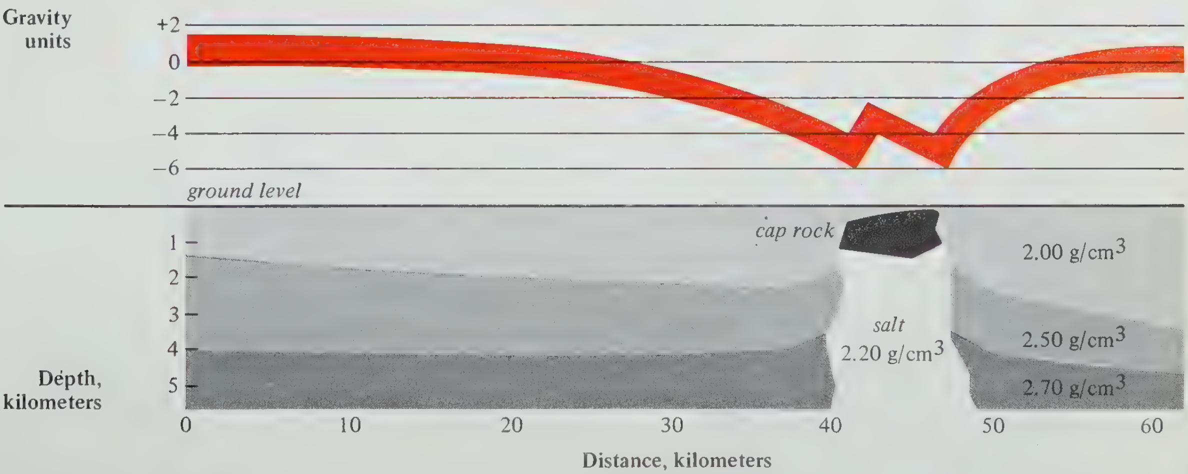
a.



b.

Figure 3–16

Variations in gravity-field intensity can be used to find a buried salt dome. Oil is frequently found with salt domes near the Gulf Coast.



gravity scale corresponds to the normal reading in the region. The negative values show that gravity over the dome is less than normal. The dome is capped with high density rock, which was formed on top of the salt as it pushed upward through the surrounding rocks. How does this cap rock affect the gravity values? From such measurements, geophysicists have located many salt domes and other subsurface features that could not be detected from surface evidence.

3–11 Magnetism and the earth's magnetic field

We are surrounded by another force field which includes the whole earth and extends outward into nearby space. This is the earth's magnetic field. You have probably played with the force fields of bar magnets or horseshoe magnets. Magnetic force is an attractive force under some circumstances and a repelling force under other circumstances.

A strong horseshoe magnet may pick up more than its own weight in small nails. Electromagnets used in industry will pick up many times their own weight of scrap iron. Electromagnets, however, owe their strength to a properly applied electric current.

Thousands of years ago the Greeks knew that certain types of natural materials could attract iron. The word *magnet* comes from Magnesia, an ancient city in the Middle East where rocks with the property of magnetism were found. The mineral causing this behavior in the rocks was an oxide of iron known as magnetite.

Although the ancient Greeks and Romans knew about magnetic materials, they did not know about the earth's magnetic field. Apparently, the Chinese were the first to discover that if they suspended a piece of magnetic material so that it could swing freely, it would line up in a general north-south direction. Therefore, they called one end of the magnetic material the north-seeking, or north pole, and the other the south-seeking, or south pole. The north pole of one magnet and the south pole of another are strongly attractive. Two north (or south) poles will repel each other. Either end of the magnet will attract objects made of iron and some other materials. Chinese writings of the eleventh century A.D. mention using a magnetic needle to show direction. The magnetic compass has thus been an important aid to navigation for nearly a thousand years.

Scientific understanding of the behavior of the compass did not come until the seventeenth century when William Gilbert demonstrated that the earth itself acts like a magnet and is surrounded by a magnetic field. Figure 3–17 is a cross section of the earth's magnetic field passing through the geographic (GN and GS) and magnetic (MN and MS) poles. The lines of force would appear the same in any cross section through the axis of the field. At the earth's surface the magnetic field is strongest in the polar regions and weakest along the equator. Notice that the geographic axis passes through the center of the earth but the magnetic axis does not.

A compass needle that is free to rotate in all directions will line up with the lines of force as they intersect the earth's surface. In the

Northern Hemisphere, the north-seeking end of the needle will point along the surface toward the north magnetic pole (MN). If the needle is free to rotate about a horizontal axis it will tilt, as shown by the small arrows in Figure 3–17. This tilting is known as the **magnetic inclination.** At MN the north-seeking end of the needle will point straight downward along the magnetic axis. In the Southern Hemisphere the north-seeking end of the needle will tilt upward as shown. Only at the magnetic equator will the needle be horizontal.

Figure 3–18 shows the location of the earth's north magnetic pole on Bathurst Island, about 1,900 kilometers from the north geographic pole. There is a theory that the earth's magnetic field is created by a solid ball of nickel and iron that rotates slowly inside the earth's core. The north and south magnetic poles would mark the axis of the core's rotation. It may not be a coincidence that the magnetic and geographic poles are close together. However, as we learn more and more about the earth's magnetic field, it remains a mystery.

In Figure 3–18 you can see the effect of the separation of the magnetic and geographic poles. A compass used in the eastern United States points about 10° west of geographic north. One on the west coast points 10° east, and another north of Alaska points 45° east of the geographic pole. This is known as **magnetic declination**. Along a line from Florida to the

FIGURE 3–17
A cross-section of the lines of force in the earth's magnetic field. Compare the positions of the geographic axis (GN—GS) and the magnetic axis (MN—MS).

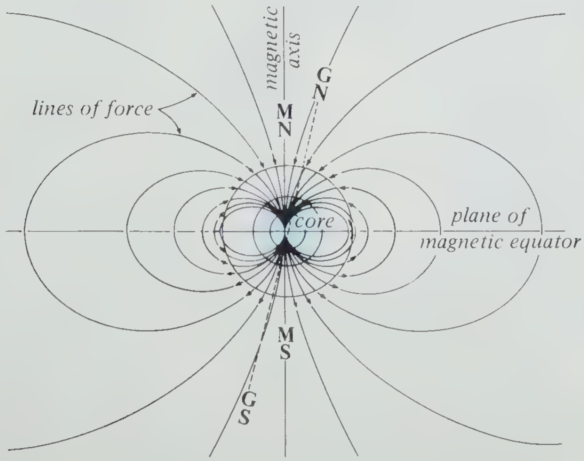
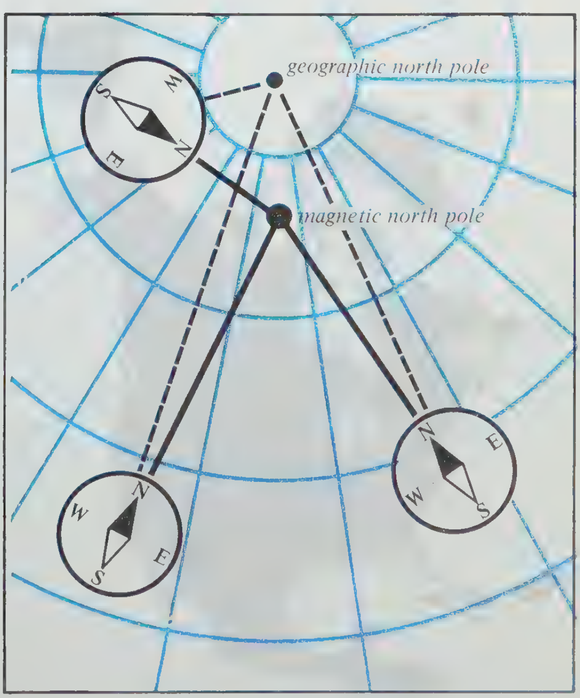


FIGURE 3–18
In the Northern Hemisphere magnetic needles point to the earth's north magnetic pole.



magnetic pole there is no declination. What would be the magnetic declination at some point on a line between the magnetic and geographic poles?

3–12
Investigating magnetic fields

Gravity is a force that affects your life in many ways. Other fields also surround you, but they are not as noticeable because their effect is not the same on all kinds of matter. One of these is the magnetic field. In this investigation you will learn more about how a piece of material with the property of magnetism influences its surroundings.

PROCEDURE

Using the equipment as shown in Figure 3–19, investigate the nature of a magnetic field. Locate the poles of the field and mark their positions on the sphere.

1. *What evidence do you have that the field is three-dimensional?*
2. *Draw a picture of what the magnetic field would look like if you could see it.*
3. *How could you distort the field?*
4. *Take a compass outdoors to a known north-south line. How does the compass indication compare to the north-south line? Explain your observation.*

3–13
Changes in the magnetic field

The earth's magnetic field drifts slowly westward. This means that the values of magnetic inclination and declination gradually change. The change in declination is a small fraction of one degree of angle per year. This westward drift of the magnetic field is a long-term change. It is known to vary in rate between areas on the earth's surface.

Grains of magnetite are common in many rocks. As igneous rocks solidify, the poles of each grain align themselves parallel to the earth's magnetic field at the time. Grains of magnetite are also carried and deposited by streams. Many of these align themselves with the earth's magnetic field at the time they are deposited. When the rocks are solidified, the grains retain their magnetic position. Careful

FIGURE 3–19

analysis of the internal magnetism of these rocks will reveal the orientation of the earth's field when the rock formed.

Since 1945 there has been a great increase in the study of the magnetism of ancient rocks. These studies have shown that the orientation of the magnetic field, including the location of the poles, has changed with time. When rocks of the same age, say 100 million years old, are analyzed, they indicate poles widely separated from the present ones. Plotting the location of ancient poles over a span of 600 million years shows that the poles have followed regular paths across the earth's surface toward the present locations. (See Figure 3–20.) The movement of the magnetic poles suggests that the geographic poles may have moved in a similar fashion.

One recent discovery is most interesting and perhaps even more significant. In 1963 it was demonstrated that the magnetic field in some rocks is reversed with respect to that of the present. The present north-south orientation appears in all rocks formed during the last 700,000 years. During the two million years before that, it was reversed. Over the last 80 million years, the field has been "normal" about half of the time and "reversed" the other half.

Sensitive magnets also detect a variety of weak and brief variations in the magnetic field.

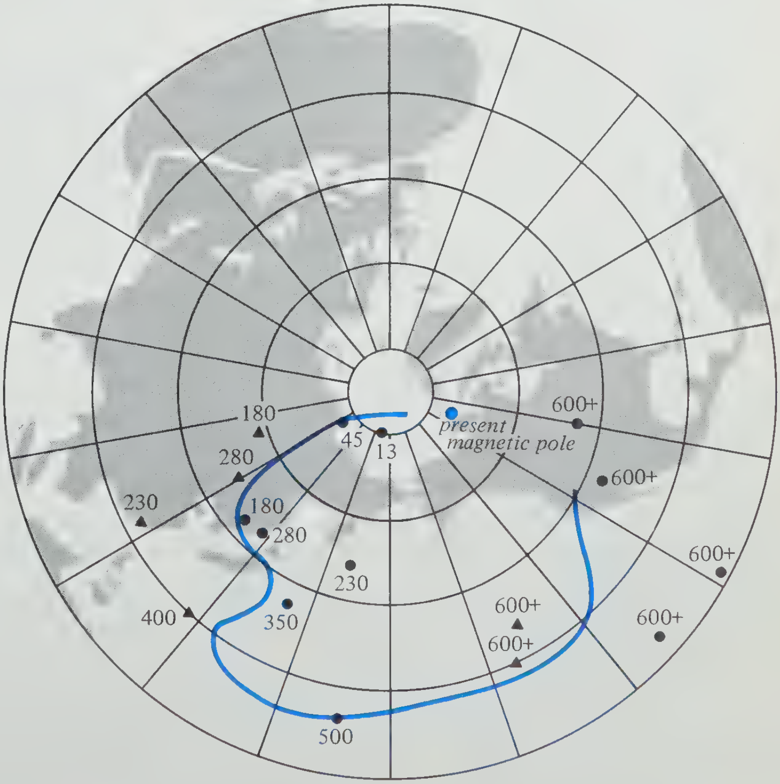


FIGURE 3–20
The apparent path of the wandering north magnetic pole. The line is based on studies of magnetism in ancient rocks. The dots represent measurements in Europe, the triangles measurements from North America. The numbers are ages in millions of years. The pole was near each numbered position at that time in the past.

These range from irregular changes with periods of a few minutes to regular and cyclic changes repeated daily, monthly, or annually. These magnetic changes are small compared to the total field strength.

Magnetic storms are strong periodic changes that last from one to several days. During a magnetic storm, the earth's magnetic intensity changes. There are increased auroral discharges in polar regions, and serious interference with radio communications. These storms seem to be related to the intensity and frequency of sun spots.

Thought and Discussion

1. How does the mass of an object affect the gravitational attraction it produces?
2. How does the distance between objects affect the gravitational attraction between them?
3. How does the shape of the earth make the attraction of gravity at the poles greater than at the equator?
4. What is gravity field intensity, and how is it useful?
5. Would you expect a buried deposit of lead ore to cause gravity to be relatively higher or lower on the surface above it?
6. Does the earth exert a pull on an astronaut in orbit?
7. Place a cube of steel or a stack of steel washers on one of the rock specimens in your classroom. What force holds the steel down? What force holds the steel up?
8. Does Newton's second law consider force as something which produces motion or something that produces a change of motion?
9. Suppose that during the reversal of the earth's magnetic field there is a period of years when there is no field at all. What effect might this have on life on the earth? If such a period had occurred in the past, how could earth scientists recognize it?

Unsolved Problems

Unsolved problems in earth science range all the way from basic questions about the nature of force and matter to problems of devising accurate measuring techniques.

What is gravitational attraction? Scientists know much about this force in terms of what it does, but no one knows why a body like the earth is surrounded by a field of force that pulls on other objects. How can one object exert a pull on another when there is no physical link between them? This question puzzled Newton, and it remains unanswered today.

You may be surprised to learn that even today we cannot make accurate measurements of the distances between continents separated by oceans. The distance between points on a single continent can be determined with satisfactory accuracy by methods that have been in use for a long time. Such measurements are accurate to 1 part in 300,000 or better. This means that a distance of 3 kilometers (300,000 centimeters) is known to an accuracy of 1 centimeter. The problem of reaching similar accuracy between points on different continents is still unsolved.

The distances between even carefully established points in Europe and America, points that have been determined astronomically, are

in error by about 100 meters. For example, we do not really know the exact distance between New York and Paris or between Paris and Bombay, India. New navigational satellites will be valuable in solving this problem. If the accuracy of measurement between such points can be increased, we may someday discover whether the continents are moving.

Another unsolved problem is why seasons vary from year to year. Why are some summers hotter than others and some winters colder than others? The seasons are caused by the motion of the earth around the sun. But this motion repeats itself year after year. Why aren't all summers exactly alike, and all winters exactly alike?

Why are there small changes in the period of rotation of the earth? We know the earth is slowing down in its rotation by one thousandth of a second per century. This slow, steady change is caused by the drag of the ocean tides. But there are other small changes—speedups and slowdowns—that happen in much shorter times. What causes the earth to be a little behind or ahead of schedule at various times?

Chapter Review

Summary

The earth has been constantly changing for a very long time—four billion years or more. All earth changes result from the flow of energy. And all forms of energy can be changed to other forms. The understanding of any process depends in part on how far you can go in tracing the flow of energy through the process.

The discussion of the earth's energy has centered around its thermal energy. The sun radiates tremendous quantities of energy into space, and the earth receives a small part of this energy. This fraction, small as it is when compared to the sun's total radiation, accounts for most of the continuing energy supply at the earth's surface.

The earth's surface radiates energy into space. A small amount of this radiated energy comes from inside the planet. Some is original heat, but most is new heat generated by the decay of small amounts of radioactive elements.

The motion of earth materials is produced by various forces. The kinds of motion a force will produce are defined by Newton's laws of motion. When a force acts at every point in a given region, a force field exists.

Two of the most important force fields in earth science are those of gravity and magnetism. Newton's universal law of gravitation describes the way the masses of two bodies and their distance apart affect the force of gravity between them. This universal law applies to all bodies anywhere in the universe. Gravity is the force responsible for most of the motions seen in nature.

The earth's gravitational and magnetic fields change from place to place on the surface of the earth. The shape and rotation of the earth affect the gravitational field. Both gravity and magnetism are affected by materials in the interior of the earth. The study of these fields gives clues about materials under the earth's surface.

Questions and Problems

A

1. Heat is transferred by the processes of conduction, convection, and radiation. Which of these processes is *most* effective in each of the examples below: (a) cooling of a cup of hot chocolate, (b) heating a skillet, (c) warming your bed with an electric blanket, and (d) getting a suntan?
2. You have often heard that machines or engines are inefficient—that they waste energy. Does this mean that the energy is lost? Explain.
3. What type of energy is always involved when a substance changes phase?
4. Why do substances containing radioactive elements tend to become warmer than their environment?
5. Since the earth radiates thermal energy, why is it not listed as a contributor to the sun's heat?
6. Is the illumination produced by a lamp a field? Explain.
7. What force, when acting on a mass of 6 kilograms, will produce an acceleration of 5 meters per second squared?
8. If velocity is plotted against time, what does a graph showing accelerated motion look like? uniform motion?
9. How is the gravitational force between two objects affected if the distance between them is doubled? tripled? halved?
10. If a force of 12 newtons acts on a mass of two kilograms, what will be the acceleration of the mass?
11. If the magnetic declination is N 13°E, is true north to the east or west of that direction? Explain.

B

1. List three examples of kinetic energy and three examples of potential energy.
2. If convection involves the transportation of energy by the material containing it, is the flow of gasoline from the gas tank of a car to the engine an example of convection?
3. Is it possible for an object or a substance to contain both kinetic and potential energy at the same time? Explain.
4. How does the fact that cold air is denser than warm air aid in the heating of the atmosphere? What would happen to the earth and its atmosphere if warm air were more dense than cold air?
5. What is the value of the gravity field intensity at a distance from the earth's center equal to twice the earth's radius? (Use 9.8 newtons as the value on the earth's surface.)

C

1. Trace the heat energy of your body back to the sun as a source.
2. Why does the bathroom floor feel cold though the rug lying on the floor feels warm?
3. What term best expresses the quantity of matter?
4. In what metric units is the quantity of matter usually expressed?
5. In these metric terms what is the quantity of matter in your body?

6. How big would a cube of granite be that contains the same quantity of matter you do? Describe some important differences between the cube of granite and your body.

Suggested Readings

Bitter, Francis, *Magnets*. Anchor Books, Doubleday and Company, Inc., Garden City, New York, 1959.

Gamow, George, *Gravity*. Anchor Books, Doubleday and Company, Inc., Garden City, New York, 1972.

Rothman, Milton A., *Discovering the Natural Laws*. Anchor Books, Doubleday and Company, Inc., Garden City, New York, 1972.

Weisskopf, Victor F., *Knowledge and Wonder*. Anchor Books, Doubleday and Company, Inc., Garden City, New York, 1963. (Paperback)

Wilson, Mitchell, *Energy*. Life Science Library, Time, Inc., New York, 1967.

unit two

The Water Cycle

4. Water in the Sea

A hill of water continuously rises behind a surfer, and his board slides down it. He races with the curl of the wave over his head. If he goes too slowly, the wave will catch up and flip him. If he goes too quickly and slides down off the wave, he'll stop moving. But the wave won't. Again he'll be flipped under tons of water. So he does his balancing act, walking up and down the moving board, adjusting its speed.

The thrill of surfing must be feeling the energy of the waves and learning to use it. Sea waves have enough energy to heat and light the largest cities, if man could only find a way to harness them. To make use of this constantly available energy remains a challenge to man's ingenuity.

The water this surfer rides off the north coast of Oahu, Hawaii, has a temperature comfortable for swimming and surfing. At one time or another, however, some of this water flowed under the ice in the Arctic. The ways in which water moves from polar seas to the Hawaiian Islands provide clues to the energy system of the ocean. Marine scientists are still piecing these clues together.

If the surfer accidentally swallows a mouthful of sea water, he will find it has an unpleasant, salty taste, different from that of fresh water. Sea water is unfit for drinking, and men adrift at sea have died of thirst. If he falls from his board, the surfer learns that he can float in the ocean more easily than in fresh water. These qualities of sea water stem from dissolved minerals.

Oceans cover most of the earth's surface and are the great reservoir of the earth's water. The atmosphere contains but a small amount of

water compared with what is stored in rivers, lakes, ground water, and ice on the land. Nor is the water stored on land for long. Water in rivers is obviously on its way somewhere. Most lakes are really wide places in a river. Even ground water and the ice in glaciers feed rivers that flow to the sea. The oceans dominate the earth's weather and climate; indeed they influence the total environment of the earth's surface.

The Ocean in the Water Cycle

4–1 The water cycle makes the sea salty.

The expression "plain water" is not truly descriptive of water. In many ways, water is a special substance. Because water exists as a solid, liquid, and gas it is one of the most active earth materials. Water is continually moving about in the atmosphere, on land, and in the oceans. It absorbs energy at some places, releases energy at others, and moves materials over the surface of the earth.

If you were to follow a water molecule around, you would learn that on the average it is in the ocean 98 out of every 100 years. The water molecule would spend twenty months as ice, about half a month in lakes and rivers, and less than a week in the atmosphere. To a water molecule, going through ice, lakes, and air is like taking a rare vacation from the ocean.

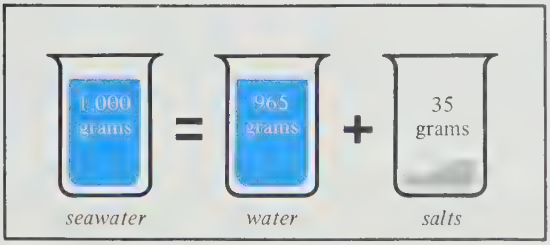
Energy from the sun evaporates sea water. Wind carries the water vapor for great distances until it condenses into clouds and falls to earth as rain or snow. The water from the rain and snow flows from tiny streams into rivers, and rivers flow back to the sea. Thus, water returns to the sea. These events are known as the **water cycle.** It is a "cycle" because the water comes back to the same place, but it has been through many changes since leaving the ocean reservoir.

In flowing across the land, rivers pick up tiny particles of soil and rock and turn muddy. Rivers also dissolve materials from their banks and beds. Almost every earth material can dissolve to some extent in water. The dissolved material occurs as ions in water. Because of gravity, the particles of rock and soil eventually settle to the bottom and are left as deposits by the rivers. Ions, however, remain dissolved in the river water, and most of them end up in the ocean.

The concentration of earth materials dissolved in sea water makes it different from fresh water. We cannot drink it or use it to directly water our crops. Sea water also corrodes most metals in a short time unless they are protected from it.

Men have known for thousands of years that if sea water is evaporated or boiled away, it leaves behind some white crystals. This was one of the early ways that men living near the sea got salt for cooking. If one kilogram of water from almost any part of the sea is evaporated, about 35 grams of solid materials are obtained. (See Figure 4–2.) The number of grams of dissolved material in 1,000 grams of sea water is the **salinity** of the sea water. The salinity of

Figure 4–1
Water and energy enter the atmosphere from the sea.



a.

b.

Figure 4–2
a. *Each kilogram of sea water contains about 35 grams of dissolved salts.*
b. *A salt lake in southern Australia.*

average sea water is about 35 grams per kilogram, or about 3.5 per cent of sea water by weight.

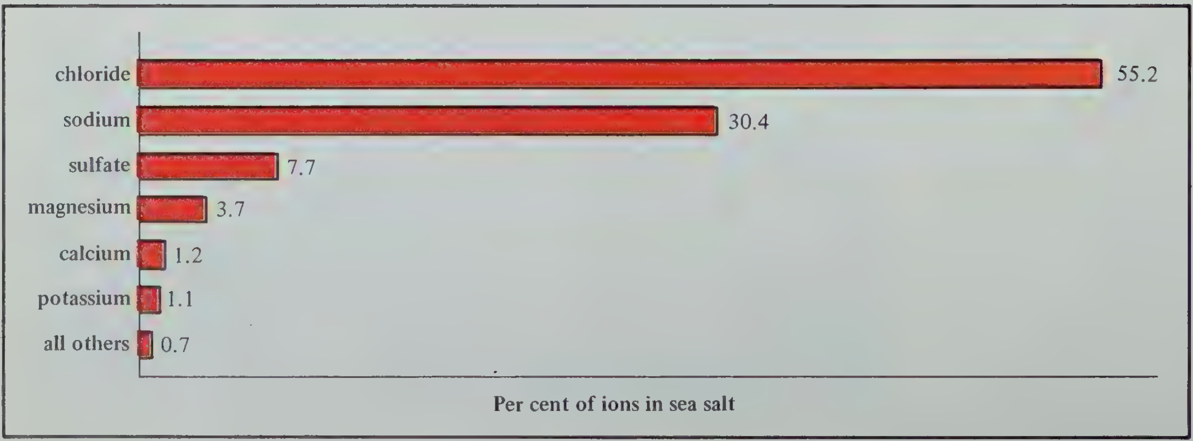
4–2 Materials dissolved in sea water

A taste of sea water shows that it contains sodium chloride, which we use as table salt. Sodium ions and chloride ions make up about 85 per cent of the material in sea water. Sensitive chemical tests have been devised to measure the amounts of about 60 other elements in sea water. However, ions of just six elements make up more than 99 per cent of the sea salts (Figure 4–3). These ions are held in solution by their attraction to the water molecules.

The composition of sea salt is different from the average composition of the earth's crust. (Refer back to Figure 2–25.) The earth is obviously not 85 per cent table salt. Some of the chemical elements in rocks and soils are much more readily dissolved than others. Once many of them get into the oceans, they are removed from the water by living organisms. Silicate minerals and calcium carbonate are abundant in the earth's crust and are washed into the oceans in great quantities. There, clams and other organisms take up the calcium and silica to make their shells and skeletons. Because of this constant use by organisms, some elements that are rare in sea water are common in marine plants and animals.

Sodium and chloride ions are so soluble that they accumulate in sea water more than others. And because they are so soluble, the ocean could hold much more of these than it does now. They are carried from the land in great quantities and are little used by sea animals. Most marine organisms have biological systems to keep excessive salt out of their bodies. We know, then, that sea water has not reached its highest possible salinity.

FIGURE 4–3
The most common ions in salt water. Scientists are not sure whether the average composition of ocean water is unchanging.



The salinity of sea water is not the same throughout the ocean. It varies from place to place and at different depths. Even so, an analysis of 77 samples of sea water collected from all parts of the world ocean during the cruise of HMS *Challenger* revealed that the most plentiful ions in sea water always occur in the same proportions. (See Figure 4–4.) This characteristic indicates how completely mixed the ocean is in all of its basins. If the amount of just one of the common ions is measured (chlorine for example), the amounts of the

FIGURE 4–4
What important finding is illustrated on this page from the H.M.S. Challenger Reports?

Challenger Number.	Date.	Station.	Latitude	Longitude	D.	δ.	Per 100 grms. of total Salts.							Alkalinity per kilo. units of V place.	Sulphuric Acid per 1 grm. of Chlorine.	Laboratory Number.
							Sea Water.	Chlorine.	SO_3.	CaO.	MgO.	K_2O.	Na_2O.			
962	1874. July 12	252	37°52′ N	160°17′ W	2740	850	2911·3	55·431	6·372	1·725	6·227	1·316	41·429	260	·11496	50
963	,, 12	252	37°52′ N	160°17′ W	2740	B—100	2940·0	55·450	6·371	1·811	6·209	1·391	41·261	218	·11490	51
1151	,, 16	...	...	...	...	200	2873·8	55·519	6·388	1·664	6·194	1·316	41·446	149	·11506	62
...	,, 17	254	35°13′ N	154°43′ W	3025	...	...	...	...	...	...	...	...	...	...	...
...	,, 27	260	21°11′ N	157°25′ W	310	...	...	...	...	...	...	...	...	...	...	...
907	,, 28	...	...	...	...	B	2895·5	55·281	6·369	1·689	6·207	1·343	41·603	399	·11521	61 & 61A
1100	Sept. 2	269	5°54′ N	147° 2′ W	2550	25	2862·1	55·412	6·437	1·706	6·251	1·331	41·367	221	·11617	343
1106	,, 2	269	5°54′ N	147° 2′ W	2550	B	2900·6	55·549	6·434	1·717	6·216	1·355	41·261	79	·11582	344
1155	,, 16	276	13°28′ S	149°30′ W	2350	B	2861·7	55·437	6·428	1·726	6·242	1·319	41·358	207	·11595	345
1221	Oct. 14	285	32°36′ S	137°43′ W	2375	B	2858·3	55·440	6·471	1·721	6·200	1·278	41·401	157	·11672	346
1259	,, 25	290	39°16′ S	124° 7′ W	2300	B	2897·1	55·478	6·429	1·701	6·209	1·336	41·366	151	·11588	347
1300	No	295	38° 7′ S	94° 4′ W	1500	B	2873·5	55·424	6·434	1·713	6·187	1·333	41·409	189	·11609	348
Mean,							.	55·414	6·415	1·692	6·214	1·333	41·433	225	·11576	
Mean, excluding Number 871 (Chall. No.).							.	55·420	...	...	...	...	...	220	...	

DISCUSSION OF THE PRECEDING TABLE.

In going over the 77 reports embodied in this table, we see that although the concentration of the waters is very different, the percentage composition of the dissolved material is almost the same in all cases; the mean values being as follows:—

(In 100 parts of Total Salts.)

Chlorine,*	55·420
Deduct basic oxygen equivalent to this chlorine,	− 12·503
Muriatic acid, $Cl_2 - O$	42·917
Sulphuric acid, SO_3	6·415
Lime,	1·692
Magnesia,	6·214
Potash,	1·333
Soda,	41·433
	100·004

* Excluding the abnormally low value in Challenger number 871.

other common ions in a sample can be determined.

Less common ions in sea water are not always in the same proportions relative to each other. Some of these ions, such as phosphates and nitrates, are used as food by organisms living in the sea, just as minerals from the soil are used by plants living on land. Near the surface of the sea, tiny drifting marine plants grow and are eaten by equally tiny animals. The less common ions in the surface waters thus tend to be used up. They are carried to deeper water when the remains of the dead, tiny animals and plants sink and decay. In this way the deep water in the ocean is enriched in the uncommon ions.

Oceanographers have not been measuring the salinity of the oceans over a long enough period of time to know whether the total salinity will change over ten's or hundred's of thousands of years. Evidence from ancient rocks and fossils indicates that the salinity of the oceans has been much the same for hundreds of millions of years.

Trace elements do vary, however, depending on the location and the time. Variations are caused by the differences in the minerals brought to the sea by streams or introduced in other ways, such as by man's activities. Such variations are always small when compared with the total volume of the ocean (1,370,323,000 km^3).

To detect these small additions to the huge volume of the oceans requires the most precise chemical tests of thousands of samples. These tests must be from samples taken over many years from all parts of the vast oceans.

Because sea water contains almost all of the elements known to man, there have been many dreams of "mining" gold and other precious metals from the sea. Ordinary salt has been obtained from sea water for many centuries. Within this century economical methods were devised to remove magnesium and bromine. All attempts to obtain other minerals from sea water have been fruitless.

4–3
The sea and atmosphere exchange matter and energy.

Most dissolved solids remain in the sea when water at the surface evaporates. However, some salt does move from the sea into the atmosphere. Breaking waves toss water droplets into the air. The smallest droplets may completely evaporate before they can fall back into the sea. The salts that were in these droplets remain in the air and are carried by the winds as tiny crystals. Eventually, moisture in the atmosphere may condense on the salt crystals and form raindrops or snowflakes.

Gases as well as solids are exchanged across the sea-air interface. The most important are oxygen and carbon dioxide. These exchanges are crucial to life, both in the ocean and on land. All plants and animals must have oxygen to live. Normally, the surface waters of the sea are saturated with oxygen. When fish or other animals use oxygen in the water, oxygen from the air replaces it. Oxygen can also pass from

the sea to the atmosphere. Marine plants release oxygen just as land plants do. Ocean currents can carry oxygen to the very depths of the oceans.

ACTION *You can see for yourself that water contains dissolved gases. Fill a tall glass or bottle with cold water and put it in a warm place, or heat it gently. Explain what you see happening.*

The most abundant material that crosses the sea-air interface is water. The atmosphere receives about 80 per cent of its water vapor from the evaporation of sea water. When the sea is warmer than the atmosphere, water vapor passes rapidly from the sea to the air. Much of this water vapor eventually condenses and falls as precipitation on some other part of the ocean or on the land.

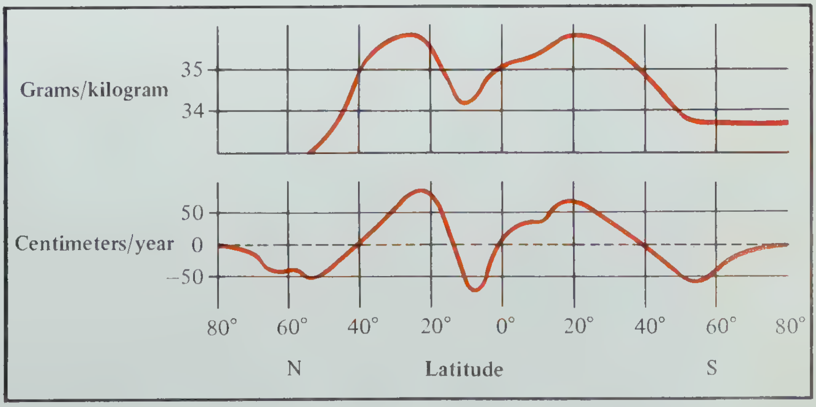
George Wüst, a German oceanographer, explained that the exchange of fresh water across the sea surface must affect the ocean's salinity. The water that evaporates from the sea contains no salts. Evaporation would increase the salinity, the percentage of salt, in the sea water that remains. Rain, in turn, would dilute the salt water and reduce its salinity. If Wüst's idea is correct, the surface of the sea should have higher than average salinity at latitudes where evaporation is greater than precipitation. Where would the salinity of the surface waters be lower than average? Look at 30° north and south latitude in Figure 4–5. Is Wüst's idea supported?

ACTION *Wet the back of one hand with water. Now wet the back of your other hand with alcohol. Can you explain the difference you feel between the two? Repeat the action and blow on the back of your hands. Is there a difference? Where did the energy come from to evaporate the water and alcohol?*

About half of the energy coming from the sun is reflected back into space or absorbed by the atmosphere before it reaches the surface of the earth. Some of the energy that does reach the earth's surface is reflected and radiated back and further heats the air.

Most of the shortwave radiation that reaches

FIGURE 4–5
The upper graph shows salinity of the surface water. The lower graph shows evaporation minus precipitation. What conclusions can you draw from comparing these graphs?



the ocean is absorbed in the top few millimeters. These are the heat-producing waves. Figure 4–6 shows how the surface water temperature varies with latitude.

Notice in Figure 4–7 that there is a surface layer many meters thick with nearly uniform temperatures near the equator. Some of the heat absorbed at the surface is carried downward into the ocean, as the waters are stirred by waves and turbulence. However, most travelers sailing on warm tropical seas do not realize that less than a kilometer away from them (straight down) the water is nearly as cold as ice. Warm surface waters do not reach these depths.

Thought and Discussion

1. How does energy from the sun change sea water?
2. Why is the composition of sea salt so different from the composition of the earth's crust?
3. Why is the sea-air exchange of carbon dioxide and oxygen crucial to life on the earth?
4. What happens to most of the energy coming from the sun?

The Sea in Motion

4–4
Waves carry energy.

Have you ever seen water completely motionless at the seashore, or in a large lake, or even

Figure 4–6
Ocean surface water temperature varies with latitude.

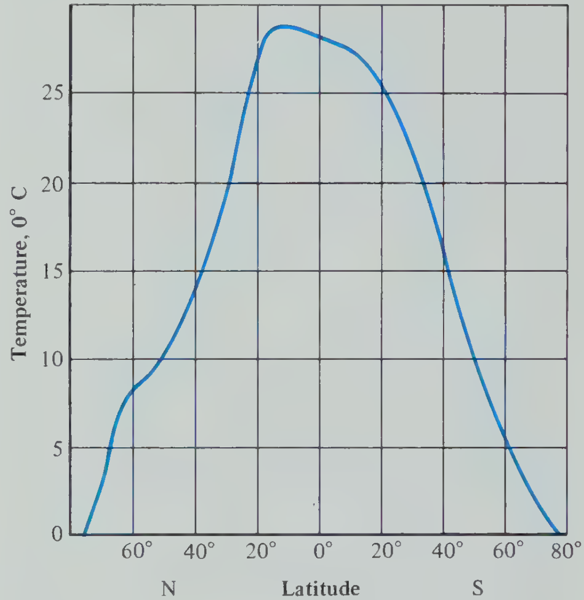
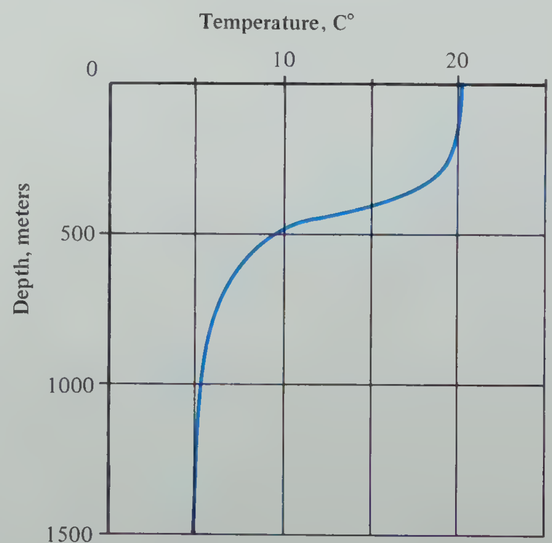


Figure 4–7
Even in tropical regions, the water in the ocean depths is very cold.



in a pond? If you have, it was not for long. Large bodies of water are constantly in motion. Mostly you noticed the waves.

The waves get their energy from the wind and carry it across the ocean to distant shores. The spectacular effects of this energy are seen on seacoasts, where waves erode the cliffs and grind the rocks into fine sand, as in Figure 4–8. If you have ever been overturned and smashed into the sand by a breaking ocean wave, you know its great energy.

Most waves in water are caused by the wind.

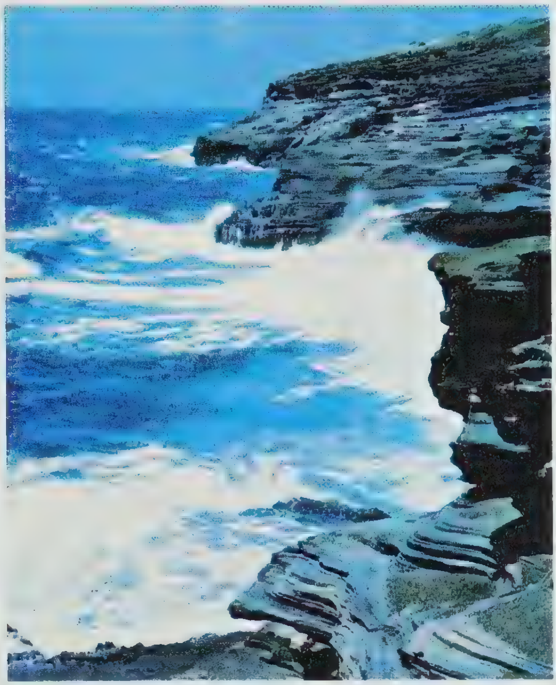


FIGURE 4–8
A storm surf crashing against the coast of Hawaii.

FIGURE 4–9
Oceanographers use wave tanks to study wave action.

If you blow on the surface of still water (in a pan), tiny ripples form. When you stop blowing, the ripples stop. The wind blows on the sea for a much longer time than you are able to blow on the water, and at sea the ripples grow into small waves. The longer and harder the wind blows, the larger the waves become. The waves will continue moving even after the wind has stopped. The wind has given them enough energy to travel hundreds of kilometers across the ocean. This is why you may see large breakers at the shore even on a windless day.

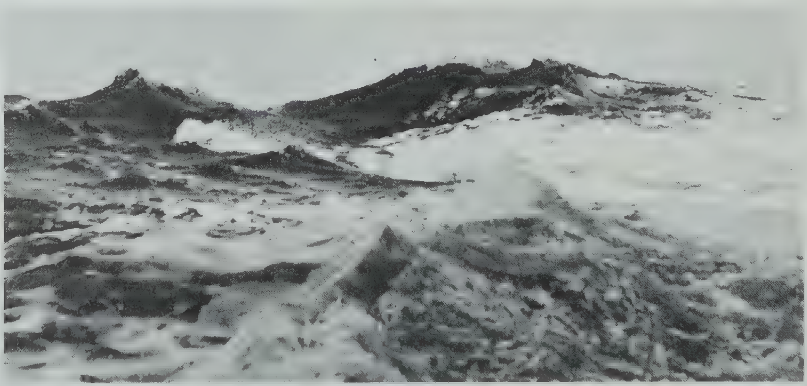
Waves on a sea or lake are usually a mixture of different heights and lengths so that no two waves look exactly alike. Some things about all waves are the same, however. Each has a top, or **crest,** and a bottom, or **trough** as Figure 4–10 shows. The height of the crest above the trough is called the **wave height,** and the distance between crests is called the **wave length.**

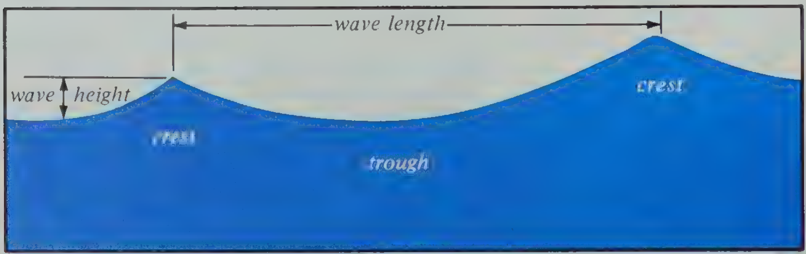
If you watch a group of waves pass a buoy or wash over a rock, you may notice that the time between crests is always about the same. This time is called the **period** of the waves. If you know the length and period of any wave, you can calculate how fast it travels. *Wave speed equals wavelength divided by period.* Thus, a wave having a length of 156 meters and a period of 10 seconds travels at a speed of 156/10, or 15.6 meters per second.

Over deep water, waves with long wavelengths travel faster than those with short wavelengths. The longer waves race ahead, leaving the shorter waves behind. They may even run ahead of the storm itself. Long, low waves crashing on a beach often warn of an approaching storm.

The speed of all waves changes with the depth of the water. When the water gets shallower, the waves slow down. Waves coming from deep water tend to catch up with the

FIGURE 4–10
The terms used to describe waves.





waves in shallow water. They do not overtake the waves ahead, but the length becomes shorter and shorter. (See Figure 4–11.) What happens to the period?

Most waves approach a beach at an angle. This means that part of a wave is in deep water and part in shallow. The part in deep water travels faster than the part in the shallow water, and the result is that the waves bend toward the beach. When waves finally reach the beach, they are almost parallel to the shoreline.

It may surprise you to learn that the water riding up and down in the crests and troughs does not move across the ocean with the waves. The water particles move, but in circular orbits. Try the ACTION hint to help you understand the principles of wave motion.

ACTION *Tie one end of a rope with a knot in the middle to a doorknob. Extend the rope to its fullest length and jiggle it from the free end. Waves will pass along the rope toward the doorknob. How does the rope itself move? What is the motion of the knot? Is this a good model of the motion of water particles in a wave?*

The water particles in waves move differently in deep water than in shallow water. Where the water is deep—deeper than one-half the length of the wave—the water particles move around in circles. The diameter of the circles are the same as the wave height at the surface of the

FIGURE 4–11
Near a beach, the part of a wave in deep water travels faster than the part in shallow water. This tends to make waves break parallel to the beach.

sea. (See Figure 4–12.) Below the surface, the water particles move in circles of smaller and smaller diameter. At a depth of about one-half the length of the wave, there is no longer any detectable motion. Submarines can easily avoid stormy seas by diving below the surface and riding in the smooth ocean depths.

In water shallower than one-half wave length, the circular motion of water particles is interrupted by the sea floor. The result is the elliptical paths in Figure 4–13. The bottom of the wave drags on the sea floor and moves more slowly than the top of the wave. This causes the wave to "break" on the beach. Breakers, or surf, throw water up on the beach with great force, carrying with it the sand and sediment that have been stirred from the bottom.

4–5
Winds cause currents at the ocean's surface.

When Benjamin Franklin was Deputy Postmaster of the American colonies, it came to his

Figure 4–12
In deep water waves, water particles (black dots) move in circular orbits. The diameter of the circle decreases with depth.

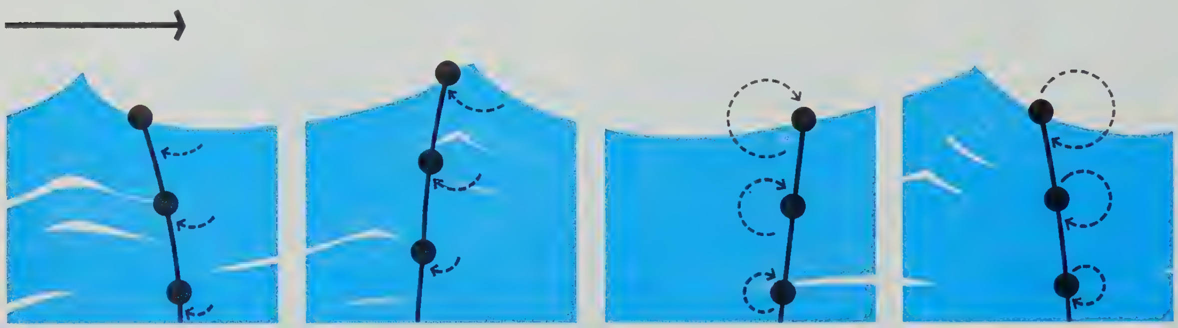
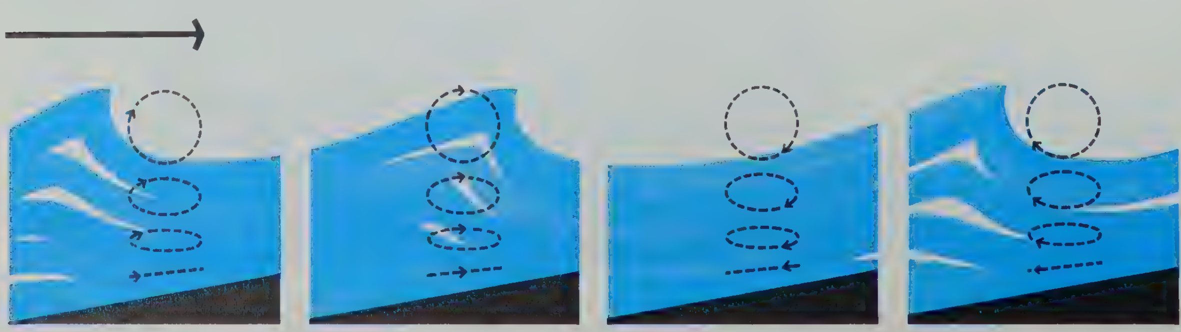


Figure 4–13
In shallow water, the bottom of a wave drags on the sea floor. The orbits of water particles become flattened into ellipses.



attention that mail boats took two weeks longer than whaling ships to make the voyage from England to America. He asked his cousin Timothy Folger, a whaling captain from Nantucket, to explain the extra speed of the whaling ships. Captain Folger replied that the whalers knew of a place in the ocean where the water flowed like a river. He went on to say that whaling captains:

. . . are well acquainted with the stream because in our pursuit of whales, we run along the side and frequently across it to change our side, and in crossing it have sometimes met and spoke with those packets [boats] who were in the middle of it and stemming [going against] it. We have informed them that they are stemming a current that was against them to the value of three miles an hour and advised them to cross it, but they were too wise to be counseled by a simple American fisherman.

Franklin asked Folger to draw a chart of this stream, now called the Gulf Stream, and had the chart printed by the General Post Office. It is shown in Figure 4–14.

Since earliest times, sailors have known of currents in the ocean, and steered their ships to use or avoid them. Yet information on currents was not collected in an organized manner until 1855, when a United States Navy officer, Matthew Fontaine Maury, compiled and published a complete collection of data on winds and currents.

Certain patterns in ocean currents became obvious from Lt. Maury's studies. You can see

Figure 4–14
Timothy Folger's chart of the Gulf Stream.

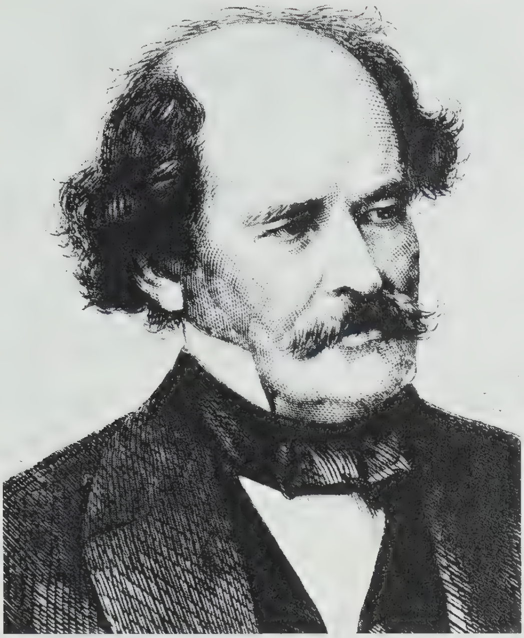
from Figure 4–15 that the currents in each of the ocean basins are similar. The water moves in large, almost circular paths north and south of the equator. These currents are somewhat like the winds. They are strong in some places and weak in others. Currents flowing away from the equator carry tropical waters to higher latitudes. (In much the same way, winds transport heat from equatorial regions toward the poles.) Ocean currents flowing along the eastern shores of an ocean basin carry cold water from polar latitudes to the tropics. You can swim in Florida waters with temperatures warmer than 30°C. At the same latitude off Baja California, the sea temperature is likely to be 15°C. The difference is created, of course, by the source of the waters that bathe the shores of the two peninsulas.

The sun is the basic source of energy for ocean currents. Of course, something must turn the sun's radiant energy into the kinetic energy of the currents. That agent is the wind. As winds blow over the sea, they exert a force on the water, just as they exert forces on trees, houses, or blades of grass on land. The water is pushed ahead of the wind in the same direction the wind blows.

The important winds that supply energy to the large currents of the ocean are the **trade winds,** which blow from the east on either side of the equator, and the **prevailing westerlies** in the mid-latitudes. Of the two, the trade winds are more constant. They tend to pile up water on the west side of the oceans, that is, against the east coast of South America in the Atlantic Ocean and against the Philippine and Solomon Islands in the Pacific. Water does not pile up well, however, so it flows downhill and escapes in large currents moving away from the equator. The famous Gulf Stream in the Atlantic Ocean

FIGURE 4–15
The general pattern of surface currents in the world's oceans. How does the circulation in the Northern Hemisphere compare to the Southern Hemisphere?

MATTHEW MAURY



One of the founders of physical oceanography was a U.S. Navy officer, Lt. Matthew Fontaine Maury (1806–1873). He measured the depth of the sea floor by dropping a cannonball tied to about a kilometer of line into the ocean off the deck of his ship. Crippled by an accident at the age of 33, Maury was forced into limited service. The Navy assigned him to its Depot of Charts and Instruments. In the Depot's dusty archives, Maury uncovered a treasure of long-neglected logbooks. These provided the initial data for a useful set of charts of the winds and currents of the earth's oceans.

Through the years, Maury obtained from sea captains the most complete set of ocean data in the world. From these worldwide observations, he compiled a famous oceanographic treatise, *Physical Geography of the Seas*. His office issued sailing instructions of great value to navigation and commerce. Maury's early observations convinced him that the oceans of the world made up a sphere "with a system of circulation as complete, as perfect and as harmonious as that of the atmosphere or of the blood."

One of the monuments to Lt. Maury's efforts to sound the sea is the Atlantic cable system. The first intercontinental telegraph cables laid in 1886 from Newfoundland to Ireland followed a route Maury had suggested years earlier.

and the Kuroshio Current off Japan in the Pacific Ocean result from this piling up of water.

Even though these large currents transport vast volumes of water, they flow slowly compared to the wind or even large rivers such as the Mississippi and the Nile. In mid-ocean the speed of a current is usually less than 2 kilometers per hour. Oceanographers become excited when they measure currents faster than this. When they do, it is generally in a narrow strait such as the one between Florida and the Bahama Islands.

4–6 Investigating the Coriolis effect

The motions of ocean currents and winds are affected by the rotation of the earth. Or rather, we should say that the earth's motion is added onto the natural motion of any freely moving objects traveling across the earth. This added motion is known as the **Coriolis effect.** It is named after Gaspard G. Coriolis, who first explained it in 1835.

The Coriolis effect can be explained by an intricate mathematical equation, but you can use the simple equipment shown in Figure 4–16 to duplicate the effect.

Procedure

Imagine that the circular tray represents the Northern Hemisphere seen from above the North Pole. The center of the tray would be the North Pole; the outside edge, the equator. By turning the tray slowly counterclockwise, you can duplicate the earth's rotation.

Erase the "Magic Slate" surface and let the ball roll down from the top of the ramp. It should make a track on the sheet. Keep the ramp in the same place. Now slowly turn the tray and roll the ball down again.

Any unattached object or material moving across the face of the earth—winds, ocean currents, and even airplanes and rockets—acts like the ball. Experiment with the equipment and try to answer these questions:

1. Is the ball deflected from a straight path everywhere on the tray?
2. Does the direction of deflection depend on which way the ramp is pointing?
3. Why doesn't the ball roll in a straight line when the tray rotates?
4. If the ball were an airplane and you were its pilot, how would you fly a straight course?
5. Suppose the tray now represents the Southern Hemisphere. Which way should you turn it, clockwise or counterclockwise?
6. How are moving objects in the Southern Hemisphere affected by the earth's rotation?
7. Which ocean currents shown in Figure 4–15 seem to be especially influenced by the Coriolis effect?

Figure 4–16

4–7
Investigating currents

Wind causes the currents at the surface of the sea, but differences in water density cause circulation in the deep ocean. In this investigation, look for the factors that affect the density of sea water. The idea is to learn how density differences cause water to move in the deep ocean.

Procedure

Set up the equipment as shown in Figure 4–17. Mix two salt solutions of different densities. This will be your artificial sea water. Pour a test tube of one of your samples of "sea water" into the large, sloping tube filled with fresh water. Measure the rate at which the salt solution travels down the tube. Put fresh water in the sloping tube and repeat the procedure with the other solution.

1. Which solution traveled down the tube faster?
2. What processes in nature could cause differences in the density of sea water?

Your teacher will give you a sample of artificial sea water. Use 100 milliliters of the solution and make it denser without adding anything to it. Try some of the methods you suggested in answering question 2. Keep a record of your methods and of the evidence that you actually have made a denser solution.

The final part of this investigation is about energy transfer and density differences. Set up a model ocean as shown in Figure 4–18. Put about 100 milliliters of ice in a paper cup that has several pinholes in the bottom. Drop a bit of paper on the surface of the water and a few bits of soaked paper inside the container. Record the temperature changes shown by the thermometers.

3. What kinds of energy transfer did you notice?

Figure 4–17

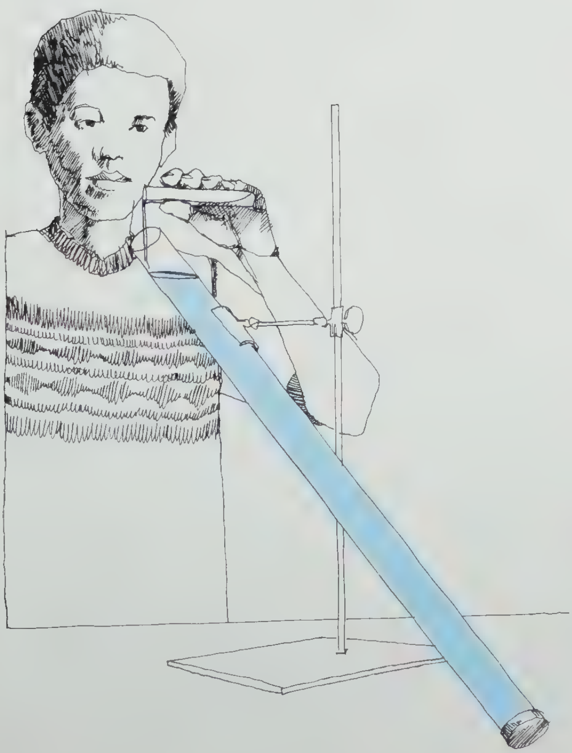
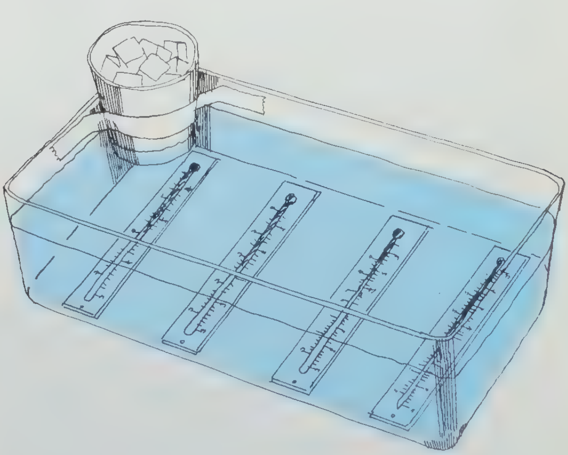


Figure 4–18



4. *If you observed evidence of currents, what was the evidence and how did the currents behave?*
5. *What caused the currents?*

4–8
Density differences and deep currents

It was once thought that the depths of the ocean were still and lifeless. Oceanographers have now taken pictures of, and even captured, animals in the deepest parts of the ocean. This means that there must be some way for water rich in oxygen to reach these great depths.

Little is known about currents beneath the surface of the oceans because they cannot be seen and are difficult to study. As recently as 1951, a new large current, the Cromwell Current, was discovered in the Pacific Ocean. A deep-flowing stream at 5,000 meters in the Antarctic Ocean was measured for the first time in 1971. These deep currents flow because of the density differences from one place in the ocean to another.

The density of sea water depends upon temperature and salinity. The transfer of matter and energy across the air-sea interface changes both temperature and salinity. Oceanographers know that deep water moves in slow currents caused by density differences. They've learned this from measurements of temperature, salinity, and oxygen in the deep water, not from many direct current measurements.

Partly because of their importance to ocean travel and fishing, currents in the Atlantic Ocean have been studied more than those in other oceans. Water circulation in the Pacific Ocean is similar to that in the Atlantic except that cold bottom water forms in the Atlantic, but not the Pacific.

The Gulf Stream carries relatively warm, salty water into the northern Atlantic Ocean off the eastern coast of Greenland. There the water cools and mixes with frigid waters flowing south from the Arctic Ocean. The result is a great increase in density. Therefore, much of the water brought north by the Gulf Stream sinks toward the bottom of the ocean. This newly formed current then moves southward into the deep ocean basins at a speed of about 20 kilometers per year. (See Figure 4–19.)

As the deep water moves gradually toward the equator, it mixes with the less salty water

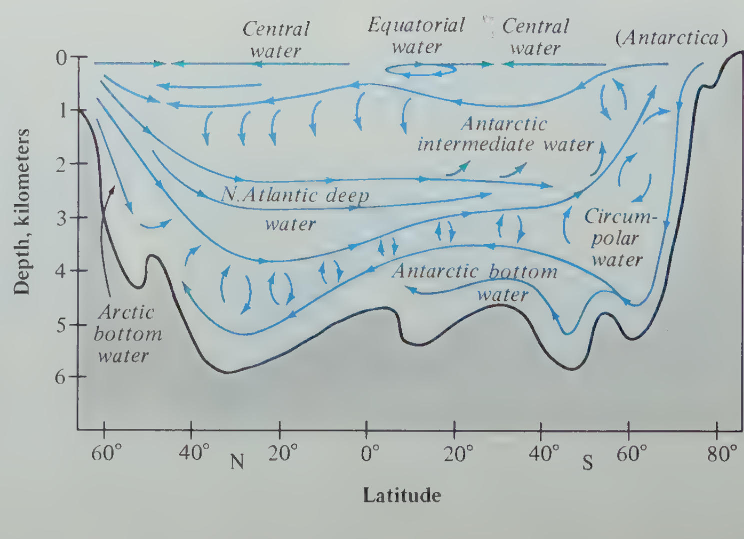


Figure 4–19
A north-south cross section of the Atlantic Ocean. Arrows mark the movement of water from the surface to the sea floor.

above it and becomes less dense. Gradually, as the water flows south past the equator, what was once deep water moves upward toward the sea surface. Finally, near Antarctica some of the mixture rises to become part of the Atlantic Intermediate Current. In this way, some water once at the bottom of the north Atlantic, returns to the north Atlantic Ocean with surface currents.

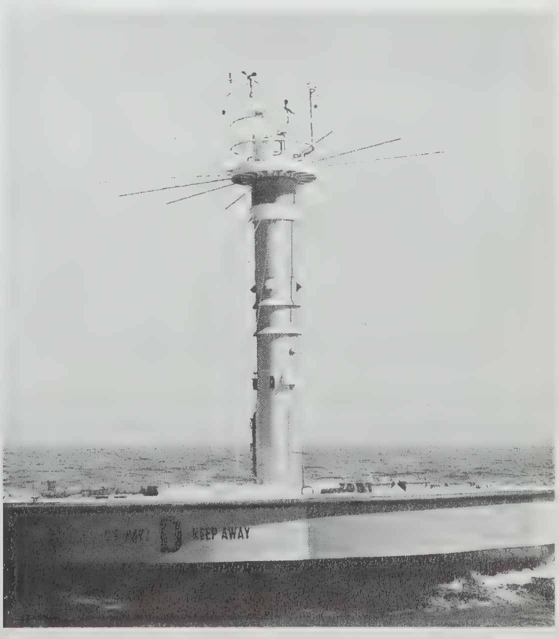
While part of the north Atlantic deep water mixes with water above it, the lowest portion mixes with the bottom water that was formed in the Antarctic Ocean. The resulting current flows around Antarctica much like the surface currents shown in Figure 4–15. Some of it eventually passes into the Pacific and Indian Oceans. In 1971 oceanographers determined that a mixture of water from the north Atlantic near Norway and the Antarctic Ocean (in the Weddell Sea) makes up much of the intermediate water in the central Pacific Ocean. This is striking evidence of the continuous mixing of waters from all the oceans.

The densest water in the ocean is formed around Antarctica. Freezing, like evaporation, leaves the salt in the unfrozen water. When sea water freezes at the surface, the salinity of the remaining water greatly increases. The high salinity and low temperatures produce extremely dense water that sinks completely to the bottom. This Antarctic water flows beneath the slightly less dense north Atlantic water, as shown in Figure 4–19. Oceanographers think that the water at the bottom of all the great ocean basins of the earth is formed in the two polar regions near Greenland and Antarctica.

ACTION *The North Atlantic Deep Current flows from the coast of Greenland downward through the Atlantic Ocean at about 20 kilometers per year, and the water begins to rise at about 30° south latitude. How long does it take the water to travel this distance? If a typical ocean has been on the earth's surface for 4 billion years, how many such trips could an individual water particle make? Would this imply that the ocean is well or poorly mixed?*

Surface currents can be measured directly in much the same way that winds are measured. Oceanographers anchor buoys with current meters in the ocean and leave them for months at a time. They record the speed of the currents, water temperature, and salinity. Figure 4–20 shows an ocean data buoy.

FIGURE 4–20
This large ocean data station also collects and transmits data on the conditions of the atmosphere.



Deep currents in the ocean are not as easily measured. There are only a few hundred measurements of deep currents, compared with thousands of readings taken at the surface. These direct measurements reveal that deep currents move as much as 100 times faster than expected for density currents. Furthermore, they change directions frequently. It appears that the deep currents of the ocean may be as changeable as the air currents of the atmosphere.

Thought and Discussion

1. Where do waves obtain their energy?
2. How does wave motion change when waves enter shallow water?
3. How does the energy from the sun generate ocean currents?
4. What is the source of deep water currents in the ocean?

Unsolved Problems

Motion in the deep ocean was thought to be slow and gentle until a number of measurements were taken over periods of two or three weeks in 1970 and 1971. Deep water, it seems may move in "fronts" and "storms," much like air masses in the atmosphere. This is puzzling to oceanographers because as yet there is no information on the source of energy for these motions.

Water becomes denser because of evaporation and freezing and sinks to the depths of the oceans to form the deep and bottom currents. If water is sinking in these great volumes, somewhere there must be equal volumes rising toward the surface. So far, no one has discovered these rising masses of water.

The most studied of all ocean currents, the Gulf Stream, still holds many mysteries beneath

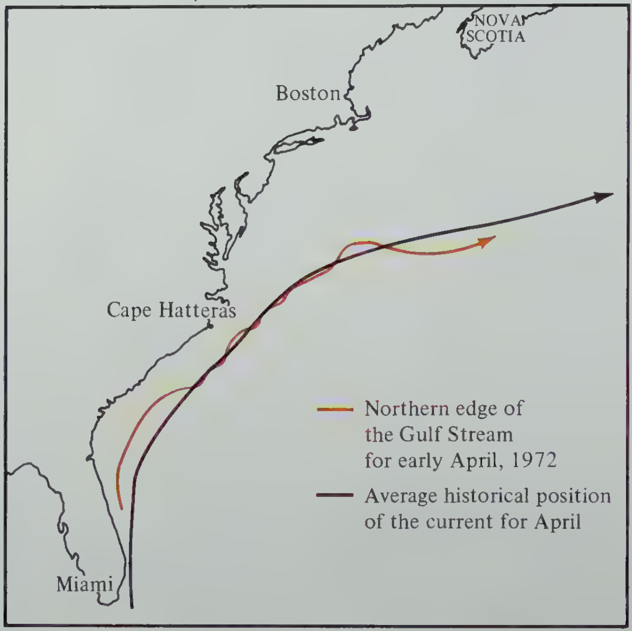


FIGURE 4–21
A map of the shifting Gulf Stream for April 1972. How does this compare with Folger's map?

its tropical water. Most ocean current charts show it as a broad stream, as we saw from the chart prepared by Captain Folger. Recent research has indicated, however, that it is actually a narrow, winding stream with many loops, as shown in Figure 4–21. For reasons that are not yet understood, the position and speed of the Gulf Stream change unpredictably from month to month.

Another question needing a more precise answer is the rate at which the sea emits or absorbs carbon dioxide. Water vapor and carbon dioxide in the atmosphere act like a blanket, absorbing some radiation from the sun and radiating some back to the earth's surface. What will happen as man continues to add carbon dioxide to the atmosphere by burning more and more fossil fuels? Some scientists think that the earth's climate may become warmer, melting the Antarctic ice and causing the sea to rise 50 meters or more. Others think that changes in the atmosphere could start a new "ice age" by reducing the amount of the sun's radiation reaching the earth's surface.

Some scientists think that no change at all will take place because the ocean and atmosphere can easily handle all the man-made additions. They think the earth has a big "safety valve" for carbon dioxide in the sea. Most of the carbon dioxide added to the atmosphere ends up in the sea. Unlike oxygen, which is mainly in the atmosphere, there is about 60 times as much carbon dioxide in the sea as in the air. You can see the need, therefore, to know how fast carbon dioxide goes into the sea. For if it is slower than we think, then it may be later than we think.

A perplexing unsolved problem became the subject of much research in the early 1970's. New analytical methods indicated the presence of heavy metals and man-made synthetics in many marine animals. Before the mid-1960's, marine scientists knew that heavy metals must be distributed in the ocean. But they had no suitable chemical methods to measure the small quantities. The new techniques showed that metals (such as lead and mercury) occurred in certain marine animals in abnormal amounts (0.5–2.0 parts per million, or 0.002 per cent). Further, chemists noted that synthetic compounds, such as chlorinated hydrocarbons (DDT) and polychlorinated biphenols (PCB) were in the tissues of animals in the ocean as well as on land.

In 1971, a large effort was initiated by American and west European scientists to collect and analyze marine animals in the Atlantic and Pacific Oceans, and their adjacent seas. Petroleum products were included in the study, along with the heavy metals and the synthetic compounds. Early results indicated that crude oil dumped into the sea posed no permanent threat to the oceans. Although damage to beaches and destruction of birds and marine organisms may be extensive temporarily, the ocean bottom slowly recovers and repopulates. Also, the amount of mercury in fish away from the coasts is minor and apparently normal. The progress of this study will be followed with great interest by all.

Chapter Review

Summary

The quality that makes the earth unique in the solar system is the large amount of water on its surface. This water exists in all three phases: solid, liquid, and gas. Individual water molecules spend most of their time in the great world-wide ocean basin. As it goes through the water cycle, water is continually changing from one phase to another, using and releasing energy.

Water is in constant motion, carrying materials from the land to the sea. The salinity of the ocean varies from place to place, but the most common salts always occur in the same ratios.

Waves get their energy from the winds blowing across the surface of the water. The same transfer of energy from the winds causes ocean surface currents. These currents, like the circulation in the atmosphere, carry heat from equatorial to polar regions and thereby determine the climates of the earth. The density of surface waters increases with cooling at high latitudes. This denser water sinks and produces currents in the depths of the oceans.

Questions and Problems

A

1. What is salinity?
2. In what ways does sea water differ from fresh water?
3. Discuss two ways in which energy leaves the ocean.
4. What is meant by the wavelength and period of water waves?
5. Where is most solar energy absorbed in the sea?
6. What causes ocean surface currents?
7. What causes currents in the depths of the ocean?

B

1. How do salts get into the sea?
2. About how much sea water must be evaporated to obtain 453 grams (1 pound) of sea salts?
3. What factors determine the salinity of mid-ocean surface waters?
4. Name several things that are transferred across the air-sea interface.
5. What is the speed of travel of waves having a period of 6 seconds and a wavelength of 56 meters?
6. If one-half the radiation striking the sea surface is absorbed in the first meter, and one-half the radiation that passes through the first meter is absorbed in the second meter, and so on, what fraction striking the sea surface reaches a depth of 5 meters? 10 meters?
7. What is the relation between salinity and density of sea water?

C

1. How much sea water is needed to yield 453 grams of magnesium metal?

2. Trace the flow of energy from the sun to a wave breaking on a beach.
3. What are some differences between deep and shallow water waves?
4. What causes the Gulf Stream? How was it discovered?
5. Are south-flowing currents warm or cold currents?
6. What effect has the rotation of the earth on ocean currents?
7. How would the speed and frequency of convection currents in the ocean compare with those of atmospheric currents? Explain your answer.
8. What determines sea water density?
9. How do we know about deep ocean currents?
10. How can the hypothesis that the densest water in the oceans all comes from the region around Antarctica be tested?

Suggested Readings

Blanchard, D. C., *From Raindrops to Volcanos.* Anchor Books, Doubleday & Co., Garden City, N.Y., 1967.

Coker, R. E., *This Great and Wide Sea.* Harper & Row, Publishers, New York, 1962, especially Chapters 10, 11, and 12.

Deacon, George E. R., ed., *Oceans, An Atlas History of Man's Exploration of the Deep.* Paul Hamlyn, London, 1962.

Stewart, Harris B., Jr., *The Global Sea.* D. Van Nostrand Co., Inc., Princeton, N.J., 1963.

5. Water in the Air

Four centuries ago, the great artist-scientist, Leonardo da Vinci, observed that "the air moves like a river, carrying the clouds with it." Looking at the clouds streaming through the sky on a windy day, we can imagine them as part of a limitless river that has its source in the ocean and empties upon the land. This endless river makes up the water cycle in the air.

There is **some** *water in the air everywhere. Even over the Sahara desert, the river in the air could supply a heavy rainfall. If the atmosphere were forced to give up all its water, there would be on the average an inch of rainfall over the entire earth.*

Of course the atmosphere doesn't deliver its water equally everywhere. In some areas, it supplies ample water to the land and makes it productive. In other places the water supply comes in deluges. In March, 1952, on the island of Réunion off the east coast of Africa, over 1.8 meters of rain fell in 24 hours. In many places where there is usually enough rain for crops and man's other needs, there are occasional droughts lasting a season, a year, or several years. Thus, over much of the earth's surface, a supply of fresh water is one of nature's least reliable gifts.

Why is the water carried by the atmosphere distributed so unevenly? How does water get into the air? What makes the atmosphere give up or retain its water supply? In this chapter you will investigate these questions, as you learn how water leaves the ocean and falls on the land.

Evaporation and Condensation

5–1
The water cycle

The water cycle is illustrated in Figure 5–1. Water evaporates from the ocean into the atmosphere. Winds transport the resulting water vapor over to the land, where it may condense into clouds and fall as rain or snow. The water then flows over and through the land back to the ocean. This is a description of the main path of the water cycle.

The history of any particular water molecule may be more complicated. For example, rain falls upon the ocean as well as the land. And water evaporates from the land as well as from the ocean. Perhaps you have seen thin clouds of moisture rising from a freshly ploughed field, or watched the mist rising from warm city streets after a rain.

The water cycle occurs on many scales. A puddle of water that you watch evaporate today may fall on you tomorrow in a shower. Sea water evaporated from the Caribbean a week ago may be the snow falling today over New England. Many large and small exchanges of moisture between land, sea, and air make up the overall water cycle.

Water naturally occurs in three phases. As it moves through the water cycle, it continually changes from one phase to another. In winter, for example, puddles of water freeze, then melt, and within a day or two evaporate. If you observe the clouds closely, you can see the same processes going on much more rapidly in the atmosphere. You cannot see the water vapor, but you can see evidences of evaporation as clouds disappear.

5–2
Investigating evaporation

Clothes on a line dry faster on a sunny day than on a cloudy day. Yet when it is sunny, the air may also be windy or calm, moist or dry. Which of these factors affect evaporation and influence the water cycle? One way to find out would be to place a pan of water in the open air. You could then compare the amount of water that evaporates with the weather at the time. However, when several factors are acting at the same time, such as wind and sun, it is difficult to separate the effect of each factor. In the classroom laboratory you can study the effect of one variable at a time on evaporation.

FIGURE 5–1
A simplified diagram of the water cycle.

PROCEDURE

A balance, some sponges, a lamp, a fan, plastic bags, and hot and cold water are available. (See Figure 5–2.) Use whatever supplies you need to investigate evaporation. Try to determine the effect of one variable at a time. Then answer these questions:

1. What factors influence the rate of evaporation?
2. Which of these factors has the greatest effect?
3. How do these factors operate in nature?

5–3
Investigating energy changes during evaporation

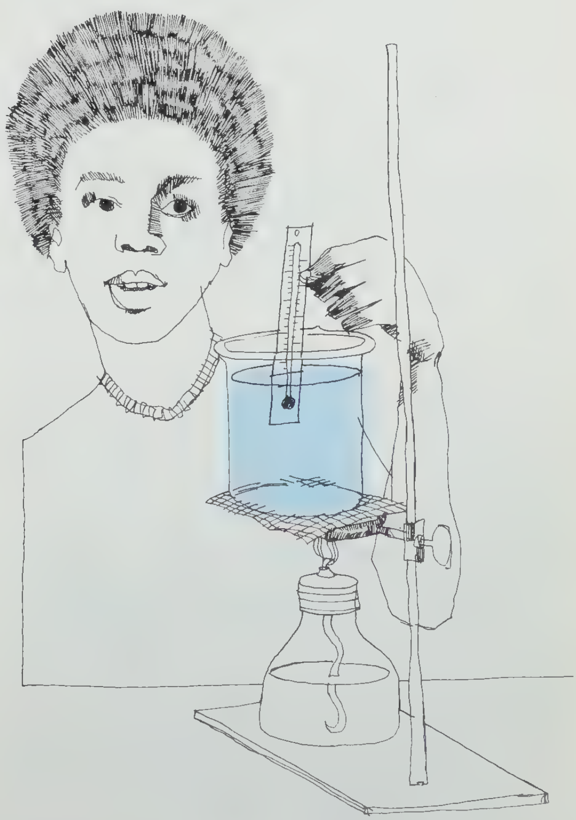
In Investigation 5–2, you may have concluded that shining a lamp on the sponge made the water evaporate faster. This suggests that heat makes water evaporate. Is energy (heat) also used in melting? You can find out what energy changes go on during melting and evaporation in this investigation.

PROCEDURE

You will need a beaker of crushed ice, a Bunsen burner or a hot plate, and a high-temperature thermometer. Set up the equipment as shown in Figure 5–3. While stirring the ice **gently** with the thermometer, read and record the temperature at one-minute intervals. Add heat until the water boils and then make three more

FIGURE 5–2

FIGURE 5–3



readings. Graph your results. Then try to answer these questions:

1. *How does the energy going into the beaker affect the temperature?*
2. *When did the greatest temperature changes occur?*
3. *What do you think caused the changes in the slope of the line on your graph?*

5–4
Melting and boiling

During melting and boiling in Investigation 5–3, the temperature stopped rising, even though you kept adding heat. The heat was used to change the ice to water and later the water to vapor. This heat energy that is absorbed during changes of phase is called **latent heat.** "Latent" means hidden or potential. It is "hidden" because it doesn't change the temperature of the water.

The exact amount of heat that is absorbed when a piece of ice changes to water at 0°C is given off when the water freezes at that temperature. Similarly, the amount of heat used when water evaporates is the same amount released when the vapor condenses back to water, if the temperature remains the same. Thus you can think of latent heat as potential energy stored in the liquid or gas.

Latent heat is not an easy concept to understand, but this explanation will give you the basic idea. The water molecules in ice are fairly rigidly bound together. The energy absorbed by ice during melting is used to break up the rigid arrangement of molecules. Once this is done, the water molecules can move more freely and slip and slide over each other. The bonds between them are weak. It takes another supply of energy for molecules in a liquid to break those bonds and exist as vapor.

When water boils, bubbles of water vapor appear and rise to the surface. Incidentally, these bubbles are really water vapor, which is invisible. You see the holes where the water isn't. The steam you sometimes see over boiling water, especially a tea kettle, is made of water droplets, not vapor. The vapor bubbles in boiling liquid exert enough pressure to push aside water and make room for themselves. If water is heated more strongly, there is more vapor, and the bubbles grow larger.

5–5
Air pressure and vapor pressure

The **pressure** of a gas like water vapor is the force with which its molecules strike a surface. The pressure depends on both the number of molecules and their kinetic energy. The more molecules, the more pressure. (Think of blowing up a balloon.) Also, the greater the energy of the molecules, the greater the pressure. (Hot gas can push jet planes and rockets.)

The total atmospheric pressure is about 14.7 pounds per square inch at sea level. This is the combined pressure of the water, oxygen, nitrogen, carbon dioxide, and other molecules in air on a square inch of surface at sea level. It is also equal to the total weight of the column of air that rests on one square inch of the earth's surface. At sea level, the air pressure inside us exactly balances the pressure outside, so we

don't feel this enormous pressure. At greater heights above the earth, for example on a mountain top, there are fewer molecules in the atmosphere, and less air above to press down on us. The air pressure falls as altitude increases.

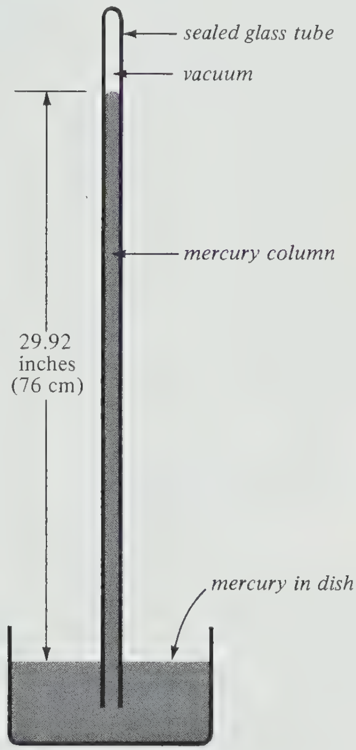
Atmospheric pressure is often measured in inches or millimeters of mercury, not in pounds per square inch. The air pressure at sea level will support a column of mercury about 30 inches high. (See Figure 5–4.) Some barometers (bah-ROM-a-ters) measure air pressure with a column of mercury, while others use a diaphragm over an air-tight can. Many in popular use are calibrated in inches of mercury as a holdover from the days when pressure was recorded in this way. The observations are now recorded in pressure units (millibars) instead of length units (inches or millimeters).

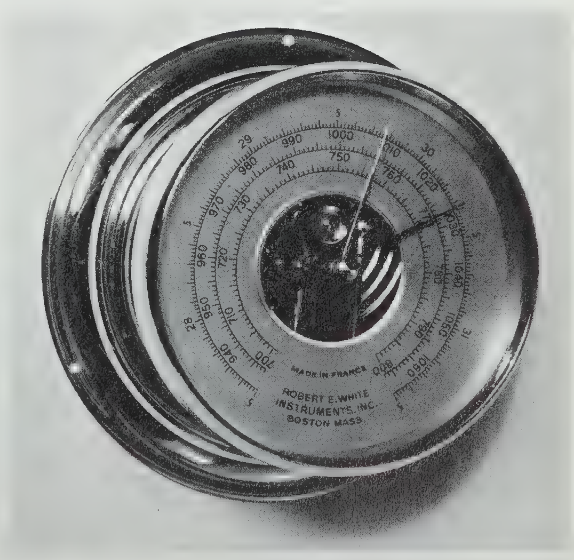
Water vapor makes up a small part of the atmosphere, generally less than 3 per cent. So the part of the total atmospheric pressure at sea level due to water vapor is normally less than ½ pound per square inch. Changes in the amount of water vapor in the air have little effect on the atmospheric pressure. Changes in pressure are determined mainly by temperature and by air motions.

Liquid water can change to water vapor without boiling. At the surface of a liquid, some molecules are always escaping into the air and some are returning to the liquid. As more molecules escape, the vapor pressure above the liquid increases. The increase in vapor pressure, in turn, causes an increase in the number of molecules that condense. If the vapor pressure is high enough, evaporation and condensation balance. Then there is no net evaporation. This

FIGURE 5–4

a. *In a mercury barometer, the weight of a column of air from the ground to the top of the atmosphere is balanced by the column of mercury.*





b. *In an aneroid barometer, changes in air pressure cause a closed container to expand or contract. The changes are measured by a pointer.*

point is called the **saturation vapor pressure.** The air is saturated and can't hold more water.

You may have guessed that the saturation vapor pressure depends on temperature. (See Figure 5–5.) The temperature at which saturation is reached is called the **dew point.** Can you explain why dew forms on grass after nightfall when the temperature begins to drop? If the temperature drops to freezing before saturation occurs, water vapor changes directly to ice. In this way **frost** is formed.

We usually think of the amount of moisture in the air in terms of **relative humidity.** Relative humidity is the ratio of the actual amount of moisture in the air to the maximum amount it could hold at the same temperature. It is expressed as a percentage:

$$\text{Relative humidity } (\%) = \frac{\text{actual vapor pressure}}{\text{saturation vapor pressure}} \times 100$$

For example, if the actual vapor pressure is 10 millibars and the saturation vapor pressure is 20 millibars the relative humidity is $10/20 \times 100$, or 50 per cent. When the relative humidity reaches 100 per cent, condensation can normally be expected.

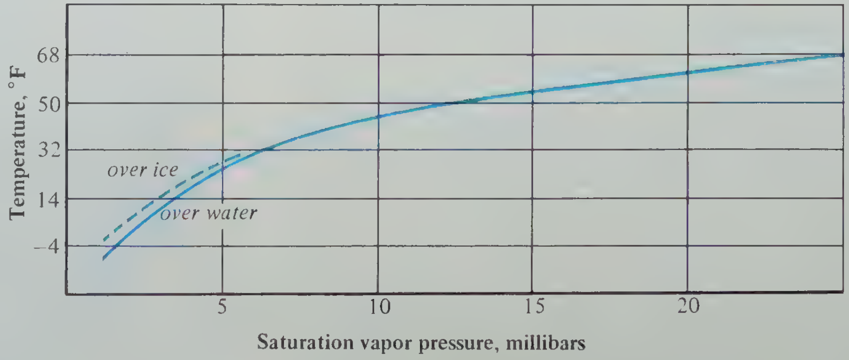
In the summer, relative humidity is a simple indicator of human comfort. When the air temperature is close to the body's temperature, we are very sensitive to differences in vapor pressure. High relative humidity slows up the evaporation of perspiration from your skin. Why does this keep you hotter?

5–6 World patterns of vapor pressure

Figure 5–6 shows that the vapor pressure over the earth is greatest at the equator and decreases toward the poles. Remember that the saturation vapor pressure increases with temperature. Most of the water vapor gets into the air across the interface between ocean and air, as you can see in Figure 5–7. Nevertheless, a great deal of water is evaporated over land as well. In fact, at high latitudes the evaporation over land is almost the same as over the ocean. And near the equator, land evaporation is greater than ocean evaporation.

Warm air above warm water usually contains much more water vapor than cold air above a dry region of the earth. However, if the air is still, a very thin layer of air directly above the water may quickly reach the saturation vapor pressure. Unless this layer is blown away, practically no evaporation takes place from the liquid surface. However, in the atmos-

Figure 5–5
The saturation vapor pressures over ice and water. Can you explain how the pressures are controlled by temperature?



phere; air is continually being moved about and mixed through a deep layer.

The rate of evaporation speeds up if the air above the water surface is dry or turbulent. Dry air is brought to the surface from higher up in the atmosphere. Dry air is also brought from the colder parts of the earth to the warmer, moister regions.

Figure 5–6
The average water vapor pressure in the atmosphere varies with latitude.

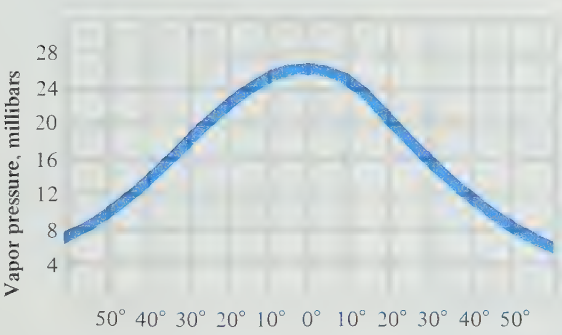
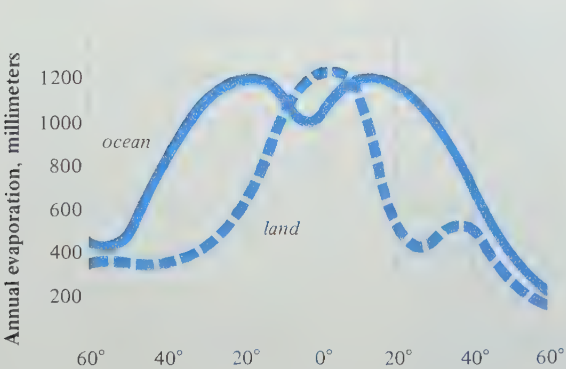


Figure 5–7
Evaporation is generally greater over the oceans than the continents, but not at all latitudes.



Evaporation takes place very rapidly when the water is warm and the air above it is dry and cold. The vapor, as it leaves the water surface, is warmer and less dense than the cold air. It therefore rises rapidly into the atmosphere by convection. (See Section 3–4.) As moist air is carried upward, evaporation continues from the ocean surface. Thus, the water cycle depends on air motions, that in turn depend on a supply of energy.

5–7
Condensation

Water vapor changes to liquid water in the air by **condensation.** This phase change is just the reverse of evaporation. The addition of heat to water increases the energy of the molecules and allows them to evaporate. When water vapor is cooled, molecules condense on the liquid surface faster than they evaporate.

Condensation is one of the necessary steps in the water cycle. It results in the formation of cloud droplets. However, cloud droplets fall so slowly that condensation alone does not take much water out of the atmosphere. Practically all of the water in the air is removed by precipitation, a process that you will study later.

Action *To investigate condensation, place a jar over a saucer of water and heat the water with a lamp. Leave the lamp on until evaporation ceases (when the water level in the saucer stops falling). Then turn off the lamp and observe what happens.*

Condensation usually occurs in the atmosphere when the relative humidity is near 100 per cent. In the ACTION above, the glass jar cools more quickly than the air inside. Water vapor condenses on the glass when the air near it cools to the dew point. If the air inside the jar cooled all at once, the vapor would condense on tiny salt or smoke particles in the air. Then you would see a cloud or fog fill the jar. The small solid particles on which water vapor condenses are called **condensation nuclei.** Air can be filtered to remove all the condensation nuclei from it. However, unfiltered air always contains some particles on which water vapor can condense.

Water vapor collects on some particles more readily than on others. It collects most easily on salt crystals left drifting in the air from ocean spray that has evaporated. Water vapor condenses on these absorbent particles at low relative humidities. All the smog and many of the fogs you see are examples of condensation at relative humidities less than 100 per cent. Dust particles also serve as condensation nuclei.

Air near the earth's surface does not often become saturated with water vapor. However, you have seen moisture condense on the side of a glass of ice water even though the atmosphere is not saturated.

Thought and Discussion

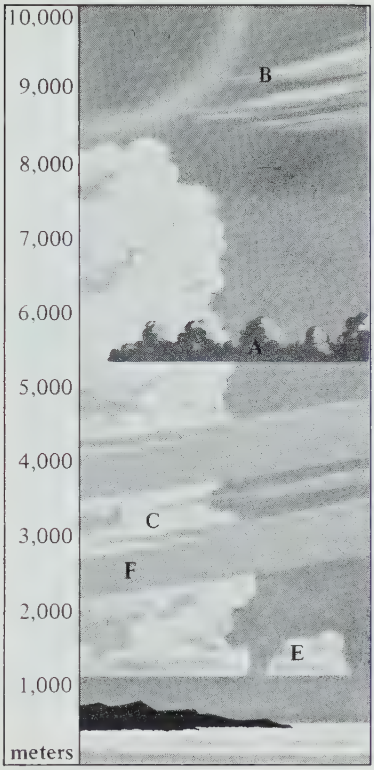
1. The curves in Figure 5–7 show the difference between evaporation over land and ocean. From your knowledge of geography, try to explain these differences. Why is the maximum evaporation over the ocean near latitude 18 degrees? What causes the dip in the ocean curve near the equator?
2. Why do you suppose that the maximum amount of water vapor in the air is only about 3 per cent of the total gases?
3. The temperature decreases as one goes up into the atmosphere. Above the equator, at a height of 17 kilometers, it has plunged to about −112°F. Above that altitude the temperature increases again. The cold part of the atmosphere over the equator has been called a "trap." How does this cold trap prevent much water vapor from getting into the warmer layer above?

Clouds, Air Masses, and Rain

5–8
Observing clouds

There are many varieties of clouds but they fall into two main types: stratiform and cumuliform. **Stratiform** clouds are sheets or layers of cloud, covering a large portion of the sky. They can contain either water droplets or ice crystals. **Cumuliform** clouds usually appear as separate puffs or towering masses. They are mainly composed of water droplets. Many clouds combine the characteristics of both stratus and cumulus clouds. (See Figure 5–8.)

The thin wisps of cloud that are found in the atmosphere are usually made of ice crystals. If you have ever seen a halo around the sun or



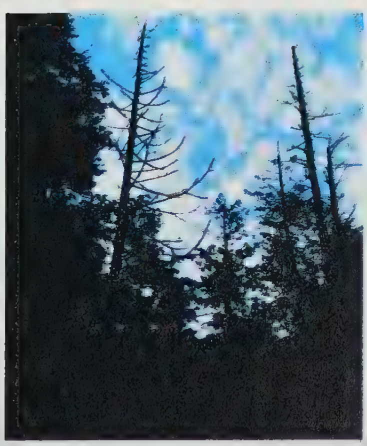
a. *altocumulus*

b. *cirrostratus*

c. *cumulus*

d. *combinations*

e. *fair weather cumulus*



f. *stratus*

moon, it was probably caused by such a cloud. The white trails made by high-flying jet planes, called **contrails**, are ice-crystal clouds (Figure 5-9). Water clouds, though white around the edges, usually have at least a faint smudge of gray at their bases.

You can observe a portion of the water cycle going on if you watch a cumulus cloud develop. When they first form, cumulus clouds look like large heaps of cotton. The flat base of the cumulus clouds marks the level where condensation begins. If they develop rapidly, they appear to boil upward. Condensation takes place most rapidly near their tops. Falling droplets evaporate in the warmer, drier air below the base.

FIGURE 5-9
Long-lasting contrails (condensation trails) are caused by water vapor from jet plane exhausts. What conditions cause the water vapor to condense high in the atmosphere?

5-9
Investigating cumulus cloud formation

In many parts of the country, cumulus clouds appear in the sky on a warm afternoon or on a cold windy day after a rain. The water vapor that forms these clouds comes from moisture-laden air rising from the ground. As the air rises, it cools. When its temperature reaches the dew point, the water vapor condenses. The dew point varies from day to day depending on the temperature and relative humidity.

Knowing the temperature and the dew point at the earth's surface, you can calculate the height at which the two become equal. This is approximately the height of the flat bases of the cumulus clouds.

FIGURE 5-10

Procedure

Find the dew point by slowly adding ice to a can of water. Gently stir the mixture with a thermometer. (See Figure 5–10.) Record the temperature when drops of water begin to condense on the outside of the can.

You can find the dew point indirectly by using the sling psychrometer as shown in Appendix B.

When air rises, it cools about 18°F for each kilometer it rises. The air's dew point also decreases, as it rises, at the rate of about 3°F per kilometer.

1. *At what height will cumulus clouds form on the day of your observations? (See Figure 5–11.)*

5–10 Clouds form in the atmosphere.

In the 16th century, Otto von Guericke, the mayor of Madgeburg, Germany, produced clouds in his laboratory. He used two flasks, joined together by a tube with valves. He pumped the air out of one of the flasks and then opened the valves. As the air expanded into the second flask, a cloud formed. Although von Guericke did not realize it, the air in his flasks cooled as it expanded. The water vapor condensed when the temperature was lowered to the dew point.

When air is compressed quickly, it is noticeably warmed. (If the compression is slow, the heat can be absorbed by the surroundings.) Just as a baseball rebounds with increased energy from a bat that is moving toward it, air molecules rebound with higher kinetic energy when the air is compressed. However, when air expands, the molecules rebound with less kinetic energy, and the temperature drops.

Suppose you take an inflated balloon high into the atmosphere. The pressure in the atmosphere decreases with height. The air in the balloon will expand because of the lower pressure around it. In the same way, an air mass moving upward in the atmosphere comes into regions of lower pressure. It therefore expands and cools.

As shown in Figure 5–11, air cools about 18°F for every kilometer it rises. (Sinking air is warmed by compression at the same rate.) However when condensation begins, rising air cools at a slower rate, about 11°F per kilometer. Condensation releases latent heat, and this heat is added to the rising air.

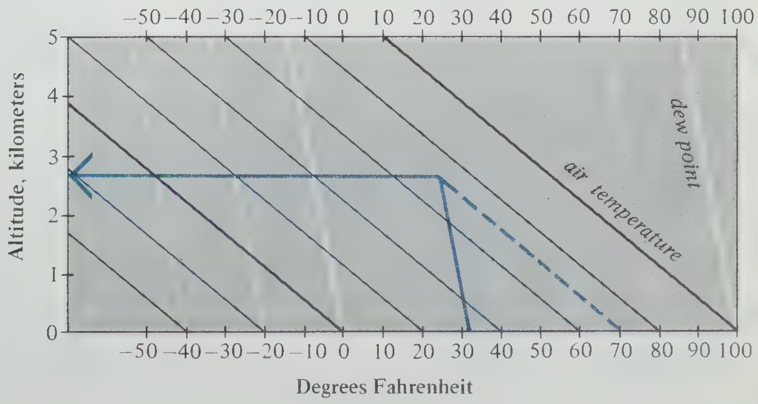


Figure 5–11
Use this diagram to find the height of cumulus clouds. For example, say the air temperature is 70° and the dew point is 32°. Read the cloud height at the intersection of the two temperature lines.

ACTION *You can illustrate von Guericke's experiment by snapping the cap from a bottle of cold soda pop, or by using the simple equipment shown in Figure 5–12. Put a little water into a two-quart wide-mouthed jar. Cover the jar and allow it to stand for a few hours. Then light a match, blow it out, and hold it for a few seconds in the jar. Re-cover the jar tightly with a rubber diaphragm that can be lifted sharply to let the air inside expand. After a few minutes pull the diaphragm sharply. Describe what happens. (If the expansion is too slow, the air may gain heat from the surroundings fast enough to balance the cooling caused by expansion.)*

FIGURE 5–12

Most condensation in the atmosphere is due to the cooling of air as it rises. However, clouds also form at the earth's surface. These low-lying clouds are called **fog.** Fog is frequently caused when cool, moist air loses heat to a colder surface below. The air cools to its dew point, and then the water vapor condenses into fog.

To summarize: moist, rising air forms clouds, but sinking air usually leads to clear skies. As air sinks, its temperature rises faster than the dew point, and any clouds in the sinking air evaporate.

5–11
Investigating an air mass

*Large areas of the earth's surface have fairly uniform temperatures and moisture: for example, the tropical oceans, the polar ice fields, and deserts. When a body of air remains over these regions for days or weeks, an **air mass** is formed. An air mass is a body of air that has nearly uniform temperature and humidity at any particular altitude.*

*The largest air masses can cover several million square kilometers, or about one-twentieth of the earth's surface. The surface below the air may be dry or moist, warm or cold. Some typical air masses are **polar continental, polar maritime, tropical continental,** and **tropical maritime.***

In this investigation you will observe in the laboratory how an air mass is formed. Your observations will help you understand how clouds (and air pollution) are related to different types of air masses.

PROCEDURE

Set up the equipment as shown in Figure 5–13. Two thermometers are used to show how temperature varies with height. At first, the temperature should be about the same at each height.

*Pour water containing small pieces of crushed ice into the outer can. Read the thermometers every three minutes until the temperature stops changing at both levels. Make a graph of temperature versus height for each observation. When the temperature has stopped changing at both levels, **gently** blow smoke through the rubber tubing into the bottom of the cylinder. Let the smoke fill about one-third of the cylinder. Then answer the following questions:*

1. *Where in the equipment is heat transferred? In what direction is the heat transferred?*
2. *Does the smoke rise in the cylinder or rest on the bottom? What is the direction of air motion?*

Exchange the can of iced water for a can of hot water. Follow exactly the same procedure as before. Read and record the temperatures in the beginning and at three-minute intervals. Watch the smoke in the cylinder as the temperatures change.

3. *In what direction does the air in the cylinder transfer heat?*
4. *Think about the movement of the smoke. Can you suggest how cumulus clouds might be produced?*
5. *What kind of air mass would probably have cumulus clouds?*
6. *What air mass would increase air pollution over cities and industrial areas?*
7. *What conditions help carry pollutants away?*

FIGURE 5–13

5–12
Why clouds differ

Cloud droplets are so small and light they almost float in the air. Slowly rising air will keep them from falling. Of course, the air's up and down motions vary a lot. This is important because different upward air motions produce different kinds of clouds.

Cumuliform clouds depend on fast upward motions. The air may rise at a meter per second or more. When air rises so fast, it tends to sink again nearby. This sinking air creates clear spaces between cumulus clouds. The up and down air motions produce a **convective cell,**

as shown in Figure 5–14. Small convective cells like those in Figure 5–15 may form when an air mass is heated from below. Tall cumulus clouds often appear in the warm, moist air in advance of a cold front. In your Weather Watch, see if you can tell when a cold front is near by observing the cloud forms.

When the upward motion of air is only a few centimeters per second, a layer of stratiform clouds may form and cover a wide area. Then the sky is said to be overcast. In your Weather Watch, look for overcast skies when a warm front is approaching.

Cumulus clouds form in some air masses but not in others, even though the moisture and surface heating may be the same. Cumulus clouds form in **unstable** air masses. The clouds that form in **stable** air masses tend to be in layers. Did you identify these two types of air masses in Investigation 5–11?

In an unstable air mass, the temperature falls rapidly as the altitude increases. When a warm parcel of air rises in such an air mass, it cools. It continues to rise as long as it is warmer and less dense than the surrounding air mass.

In a stable air mass the temperature decreases slowly, or actually increases, with altitude. If an air parcel in it is forced upward, it tends to be colder and denser than the surrounding air. Therefore it sinks.

FIGURE 5–14
A cumulus cloud can form in upward-flowing air currents. Where is air descending in this photograph?

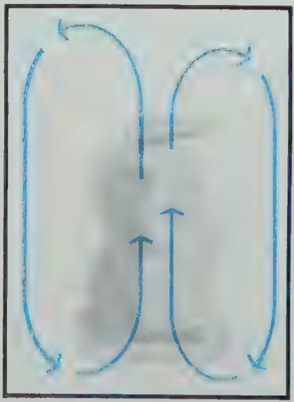
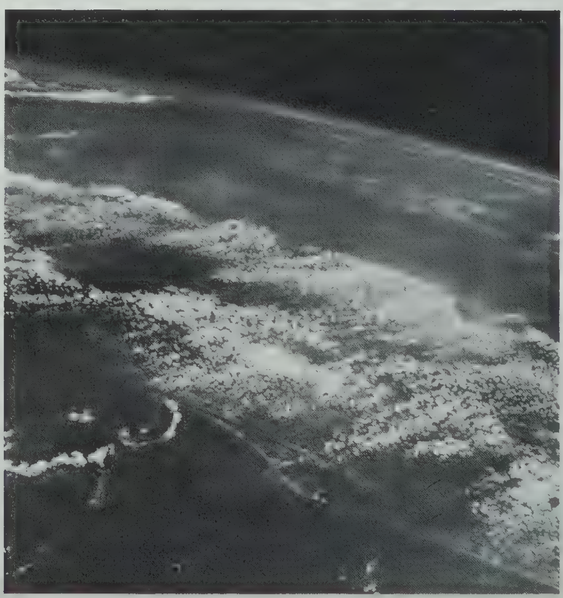
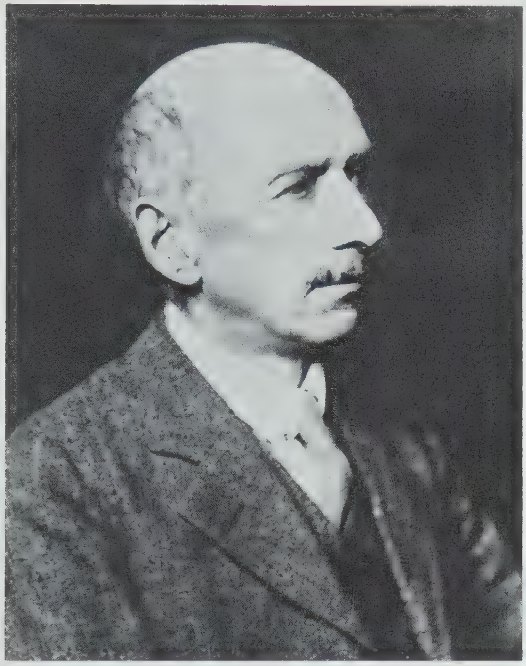


FIGURE 5–15
Cumulus clouds over Florida photographed from the spacecraft Gemini 4.





This British physicist (1869–1959), invented the cloud chamber. Wilson's first cloud chamber was a circular glass cylinder that contained a tight-fitting glass plunger. When Wilson pulled the plunger, the air was suddenly expanded, producing a cloud like the one observed by von Guericke. Wilson found that after repeated expansions, clouds no longer formed. The condensation had removed the dust particles from the air. However, when he expanded the air still more, cloud droplets appeared again. In this way, he discovered that vapor can condense on the very small electrically-charged ions in the air. This discovery led Wilson into the study of atmospheric electricity, thunderstorms, and lightning.

When Wilson sent a pulse of x rays through his cloud chamber, they left trails of condensed water vapor in the air. He was able to photograph the paths made by individual moving ions. These pictures are probably as close as we will ever get to seeing atomic particles. In 1927 Wilson was awarded the Nobel Prize for Physics for making the paths of individual electrically-charged particles visible.

At Cambridge, he worked almost entirely on his own. He had few students, perhaps because he stammered badly. The stammer made him pause so often and so long that his sentences came out slowly and painfully. As if to make up for his stammer, he described his theoretical and experimental work in elegant and lucid prose. The few students who went to his lectures knew he had valuable and well-thought-out things to say.

In spite of his wide influence, C. T. R. Wilson had little contact with other people. He was never seen surrounded by a group of students, listening and taking part in discussions. He was a good glassblower and liked to make his own apparatus. Working slowly and carefully, he spent little money on his experiments. He depended for results on long periods of thought and reasoning. Then he carried out a few careful experiments to test his thinking. Wilson has been described as one of the last of the great experimental scientists who did practically all of their work alone and yet made momentous discoveries.

5–13
Observing precipitation

Most of us are not really aware of the water cycle until it rains or snows, or hasn't rained for so long that there is a drought. Rain, snow, and other precipitation complete the airborne part of the water cycle.

The size of precipitation depends on the kind of cloud involved. The largest raindrops fall from cumuliform clouds. They can reach the size of a medium-sized pea. Raindrops larger than this can form, but they quickly break apart as they fall because of air resistance. Drizzle is composed of drops about the size of a period on this page. Drizzle falls slowly from low stratiform clouds or from fog.

Sometimes snowflakes occur as beautiful six-sided or hexagonal ice crystals. (See Figure 5–16.) Usually, the single crystals clump together into larger snowflakes. The crystals grow when water vapor accumulates on solid particles called **ice nuclei.** The water vapor goes directly to the ice phase. Particles of **sleet** (ice pellets) form when raindrops or partly melted snowflakes fall through a layer of cold air and freeze.

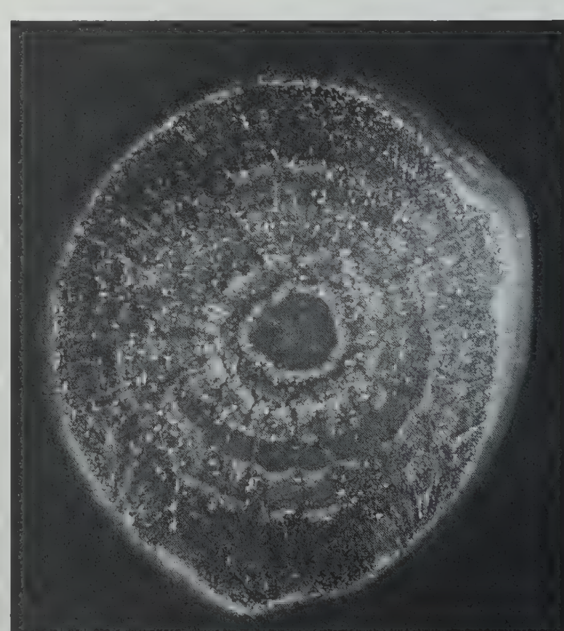
Hail is another kind of solid precipitation. It falls from cumuliform clouds. (See Figure 5–17.) Hailstones are balls or irregular lumps of ice.

5–14
How are raindrops formed?

The tiny droplets that make up clouds condense on small, solid particles. It is natural to suppose that raindrops grow by further con-

FIGURE 5–16
Although ice crystals are often pictured in perfect hexagonal shapes, they seldom occur that way in nature.

FIGURE 5–17
Cross section of a hailstone.



densation on cloud droplets. However, most raindrops cannot form in this simple way. Observation shows that it takes about a million cloud droplets to make a raindrop. (See Figure 5–18.) Condensation on a cloud droplet takes place much too slowly to increase its size a million times before the drop falls to earth.

One theory of how raindrops form involves ice crystals. Droplets and ice particles can exist in the same cloud, at temperatures well below freezing. The saturation vapor pressure over an ice particle is lower than the saturation vapor pressure over a cloud droplet at the same temperature. (See Figure 5–5.) Water vapor in the surrounding air tends to crystallize on the ice crystals rather than condense on the water droplets.

FIGURE 5–18
The relative sizes of a cloud droplet, a drizzle drop, and a raindrop.

The loss of vapor in the air causes more water to evaporate from the cloud droplets. The vapor continues to crystallize on the ice particles, and they grow rapidly and become snowflakes. These flakes may melt in lower, warmer regions of the atmosphere and fall as rain. If they do not melt as they fall, the particles reach the ground as snow.

The temperature of many clouds is above freezing. There can't be ice crystals in these warm clouds; yet rain often falls from them. Raindrops can form in warm clouds if the cloud droplets collide and stick to each other. Raindrops grow fastest when there are drops of many different sizes colliding. Collisions between droplets are favored when the clouds are tall and convective movements are strong.

Thought and Discussion

1. Meteorologists can make some cumulus clouds grow very rapidly by dropping silver iodide particles into the cloud tops. The silver iodide particles serve as nuclei on which ice crystals can form. In effect, the experimenters are turning part of the water cloud into ice. The meteorologists point out that this change of phase makes the cloud warmer and causes it to develop. Explain how this can happen.
2. How is precipitation different from condensation?
3. If the earth's surface were all ice, what would the water cycle be like?

Unsolved Problems

In 1946 scientists demonstrated that dropping dry ice or silver iodide particles into certain clouds could change them. The clouds had to contain supercooled water (droplets with temperatures below freezing). Since then, many carefully-designed experiments have shown that, *under certain conditions*, clouds "seeded" with particles yield about 10 to 20 per cent more precipitation than unseeded clouds.

Layered clouds formed in moist air rising over mountains have given the most consistent results. The results from seeding cumulus clouds are less clear-cut. In an experiment over Arizona, the seeding of summer cumulus clouds apparently caused a decrease in rainfall. But cumulus clouds in moist tropical air masses in and near Florida have been made to produce more rainfall by seeding. Scientists were able to select tropical cumulus clouds that could be successfully seeded by making measurements from airplanes.

In spite of modest successes, after years of experimentation, weather modification by cloud seeding remains a largely unsolved problem. Scientists cannot yet specify for the world as a whole the best kinds of clouds, locations, and times of day and year to produce more rainfall.

Some of the variables that may determine the success or failure of seeding are the following: the stability of the cloud and the air mass, the kinds and number of ice nuclei present, and the effect of latent heat, released by seeding, on the growth of the cloud. Moreover, experiments to cause more rainfall from warm clouds (water droplet temperature above freezing) have been relatively unsuccessful, compared with those involving supercooled clouds. To cause cloud droplet growth in warm clouds, water absorbent materials such as sodium chloride, calcium chloride, and urea have been tried.

Chapter Review

Summary

Man looks to the shallow reservoir in the air for his supply of fresh water. This reservoir is constantly refilled from the ocean's surface water. The atmosphere acts as a pump and a condenser of water vapor, moving the water from the ocean to the land.

Evaporation is controlled primarily by energy. However, air motions are necessary to remove the vapor so that evaporation can continue. Upward motions lift the water vapor into regions of lower atmospheric pressure, and the winds transport evaporated water to the continents. As the vapor expands, it cools and condenses. Energy is stored as latent heat in the vapor. Condensation releases this energy. The latent heat adds to the energy of storms and in this way intensifies the water cycle.

Water vapor condenses to form clouds. Cumuliform clouds are usually produced by the small-scale, rapid updrafts caused by convection. Stratiform or layered clouds are usually produced by the gradual upward movement of air masses. Air masses are large bodies of air

that have nearly uniform temperatures and humidity. The air masses acquire these properties at the earth's surface.

After cloud droplets are formed, the water still has to collect in large drops or crystals to form precipitation. Raindrops can be formed in two ways. Vapor in the cloud can crystallize on ice particles that melt as they fall to earth. In warm clouds, only the collisions of droplets can account for the growth of raindrops. This process may also operate in colder clouds.

The energy that powers the atmosphere's circulation and the water cycle comes from the sun. The following chapters show how solar energy reaching the earth causes the air motions that carry water from the ocean to the land.

Questions and Problems

A

1. Describe some of the different pathways in the water cycle.
2. Why is temperature an important factor in evaporation?
3. If the actual vapor pressure is 15 millibars and the saturation vapor pressure is 20 millibars, what is the relative humidity?
4. What is the main cause of condensation in the atmosphere?
5. What are the two main processes that start the formation of raindrops in a cloud?

B

1. The air temperature is 70°F and the dew point is 32°F. About how high must the air be lifted to reach saturation?
2. A rapidly moving cold front is pushing unstable, tropical, maritime air ahead of it. What kind of clouds would you expect to find in the air just ahead of the front?

C

1. Why do earth scientists speak of *the* water cycle, when water goes through so many different cycles?
2. The air temperature at the earth's surface is 70°F, and at 3 kilometers it is 35°F. If you could carry a balloon containing air to 3 kilometers, would the temperature of the air in the balloon be warmer or colder than the surrounding air?

Suggested Readings

Battan, Louis J., *Cloud Physics and Cloud Seeding.* Doubleday & Company, Inc. (Science Study Series), New York, 1962. (Paperback)

Battan, Louis J., *Radar Observes the Weather.* Doubleday & Company, Inc. (Science Study Series), New York, 1962. (Paperback)

Blanchard, Duncan C., *From Raindrops to Volcanoes, Adventures with Sea Surface Meteorology.* Doubleday and Company, Inc. (Science Study Series), New York, 1962. (Paperback)

Leopold, Luna B., Davis, Kenneth S., and the editors of *Life, Water.* Time, Inc. (Life Science Library), New York, 1966.

Thompson, Philip C., O'Brien, Robert, and the editors of *Life, Weather.* Time, Inc. (Life Science Library), New York, 1965.

6. Energy and Wind

From early times, scientists have looked for patterns beneath the apparent aimlessness of the winds. In the 17th century, maps of the winds were pieced together from ships' logs. These early maps showed broad belts of winds over the tropical oceans—called the trade winds—that were constant in direction and speed. The maps also showed winds that blew into the land in summer and away from the land in winter. Sailors called them monsoons.

Aristotle believed that the winds are produced by a kind of "breathing" of the earth. In 1686, Aristotle's ideas about wind were still popular. Dr. Martin Lister of the British Royal Society suggested that the trade winds are "constant and uniform" because they come from the breath of only one kind of plant: the seaweed of the tropical ocean. The land winds are confused—blowing from no single direction—because they are "exhalations" of many different kinds of plants. The ideas seem foolish, but you could easily make observations that might seem good evidence for them.

In the same year, however, another British scientist published the first map of the winds of the world and explained them in terms that we accept today. Edmund Halley pictured the trades and the monsoons as the surface flow of huge convective circulations, caused by temperature differences on the earth. He realized that the sun drives the winds.

The Earth's Energy Balance

6–1
Investigating radiant energy

The water cycle depends on water in all three phases. Suppose the earth were so cold that its entire water supply was locked up in ice, or so hot that all the water had turned to vapor. Then the water cycle as we know it would no longer exist.

The temperature of the earth's surface and of the atmosphere varies within a fairly narrow range. This range of temperature makes it possible for water to occur in all three phases. What determines the earth's temperature? That's what you can investigate now.

Procedure

Set up the equipment as shown in Figure 6–1. Read and record the temperature in each can before the lamp is turned on. Call this the beginning temperature (BT). Turn the lamp on and observe the temperature in each can until it stops rising or becomes stabilized. Record the stabilized temperature (ST) for each of the four cans.

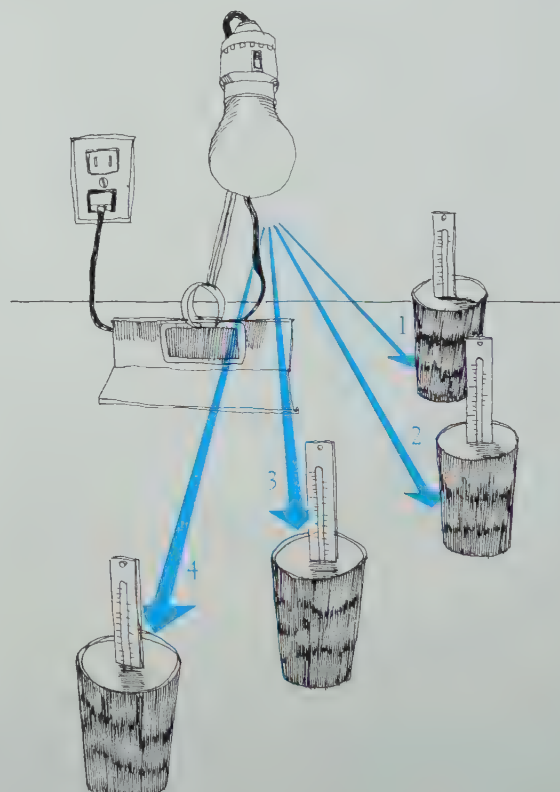
1. *Why did the temperature eventually stabilize?*

*Subtract the beginning temperature (BT) from the stabilized temperature (ST) to find the observed **change** in temperature (OTC) caused by the lamp's radiation (ST − BT = OTC). Plot the change for each can on a graph. Make one axis of the graph the temperature change, and the other axis the distance between the lamp and the cans. Connect the points on your graph with a smooth curve.*

2. *What is the relation between the temperature change and the distance of each can from the lamp?*

*You can think of the lamp as being at the center of an imaginary hollow sphere, like a point of light within a beach ball. The light radiates energy equally in all directions. Therefore, its energy is spread equally over the inner surface of the beach ball. Now imagine a still larger beach ball surrounding the light. **The same amount of energy is now spread over a***

Figure 6–1
The numbers are distance units from the light to the can.



much larger area. Therefore, the energy received on one square centimeter of the larger ball is less than the amount received on one square centimeter of the smaller ball.

*It can be shown that the temperature **change** produced by the lamp depends on distance in the following way:*

$$\text{Calculated temperature change of can} = \frac{\text{observed temperature change of nearest can}}{[\text{distance to can (d)}]^2}$$

or

$$CTC = \frac{OTC_1}{d^2}$$

In the formula, $d = 2, 3,$ or 4. *It is expressed in multiples of the distance from the lamp to the first can. Plot the calculated temperature changes (CTC) for the four cans on the same graph on which you plotted the observed temperature changes.*

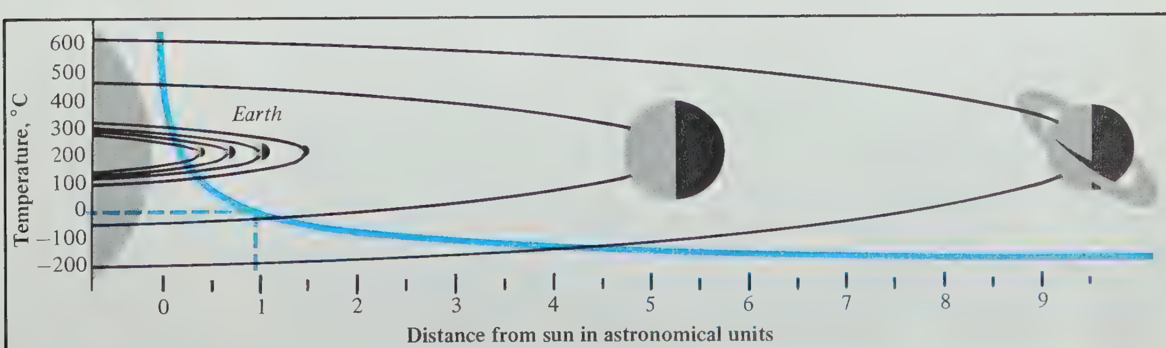
3. *Do your observed temperature changes agree with those calculated from the formula?*
4. *Figure 6–2 shows how the temperatures of the planets decrease with distance from the sun. Would most of the earth's water be solid, liquid, or gas if the earth were one-half its present distance from the sun? Twice its present distance from the sun?*

6–2
Earth's energy balance and distance from the sun

The amount of energy the earth gets from the sun is nearly constant. The earth's distance from the sun varies a little during the year because the earth's orbit is not exactly a circle. The earth is farthest from the sun in early July and closest early in January.

During the past century, scientists have observed the sun's energy output to see if it changes. The presence of the atmosphere makes it impossible to determine whether changes in the amount of energy received on earth represent actual variations in the sun's output. But astronomers have observed changes in brightness of the planets Neptune and Uranus. Their

FIGURE 6–2
If the planets absorbed and emitted all the solar energy reaching them, they would have the temperatures shown on this curve. One astronomical unit is the average distance from the sun to the earth.



observations show that over periods of 10 or 20 years, solar energy cannot have changed more than one per cent. A one per cent change in the sun's energy output could cause the earth's temperature to change about 0.6°C (1°F).

There is evidence that in the past 60 million years the earth's average surface temperature fell from a warm 20°C to about 12°C (68°F to about 54°F) when the advance of ice sheets reached a maximum. Over the past few centuries, however, the surface temperature has varied only a little from its average of 15°C (59°F). This suggests that the earth now emits (puts out) about the same amount of energy it absorbs from the sun.

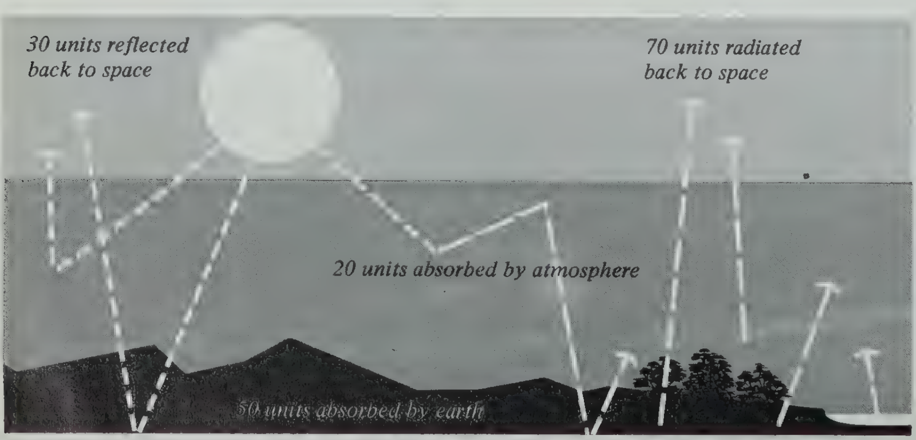
When an object emits as much energy as it absorbs, it is in **radiative balance.** Changes from 20°C to 12°C suggest (but do not prove) that the earth's surface has not always been in radiative balance. At times it may have slowly stored heat energy, and at other times slowly lost heat. Many possible causes have been suggested for the earth's wide swings of climate, but there is no general agreement among scientists about what causes climatic change.

6–3 The atmosphere and the earth's energy balance

Very hot objects like the sun emit **short-wave** radiation. Cooler objects emit **long-wave** radiation. About half of the solar energy is short-wave radiation that we see as light. This energy passes through transparent substances. In contrast, the earth emits long-wave radiation. Long-wave radiation is felt as heat. You can feel heat radiating from pavements, the soil, and other surfaces in hot weather.

Materials are affected differently by energy from the sun. For example, a window pane *transmits* sunlight. It is nearly transparent, and much of the short-wave solar energy passes

Figure 6–3
The energy budget of the earth and its atmosphere. Some energy is reflected directly back to space from the atmosphere and earth. The remaining energy is first absorbed and finally radiated back to space.



through. Only a little energy is *absorbed* to heat up the glass. However, the walls and furniture inside a room absorb a large part of the solar radiation coming through the window. *The energy radiated from the furniture, unlike the original solar energy, is all long-wave radiation.* Much of it is unable to pass through the window pane. Try putting a piece of glass in front of a hot object to see how the heat waves are cut off. A greenhouse traps heat energy in this way, and so does the atmosphere. This phenomenon is called "the greenhouse effect." The atmosphere, like the glass, does not transmit the earth's long-wave radiation as readily as it transmits short-wave solar radiation.

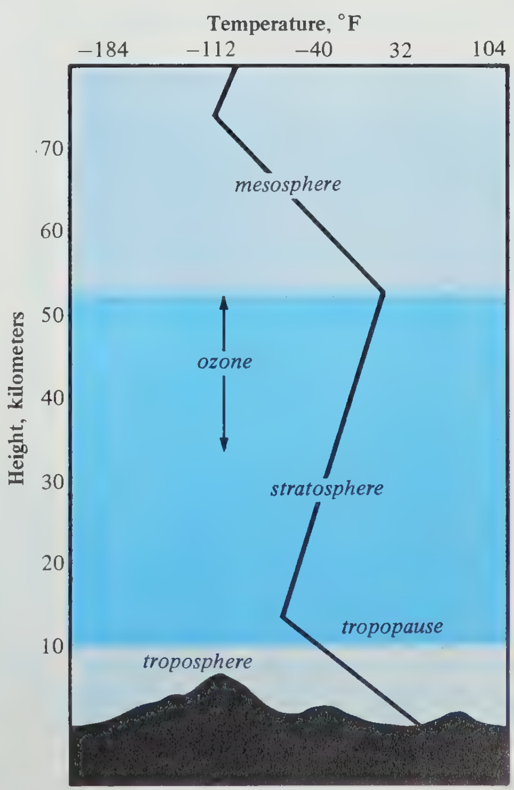
It is mainly the water vapor concentrated in the lower part of the atmosphere that acts like a window glass. The water vapor is nearly transparent to sunlight coming in. However, the vapor absorbs much of the long-wave radiation going out and coming in. The vapor sends some of this radiation back to the earth's surface. (See Figure 6–3.)

Carbon dioxide in the atmosphere acts like water vapor. It also transmits most of the short-wave energy *to* the earth's surface and absorbs long-wave energy *from* the surface. Like water vapor, carbon dioxide radiates some of this long-wave energy back to earth and transmits a little upward through the atmosphere.

High in the atmosphere is another absorbing gas called ozone (O_3). Ozone does *not* act like glass in a greenhouse. It is vitally important to us because it absorbs practically all of the **ultraviolet radiation** from the sun. This is very short-wave radiation of high energy. Even the small amount of ultraviolet radiation that passes through the atmosphere can give you a severe sunburn. If too much ultraviolet radiation reached the earth's surface, life as we know it could not exist.

A large part of the atmosphere is sandwiched between these two good absorbers, the earth's surface and the ozone layer. Notice in Figure 6–4 how the temperature first decreases above the earth's surface and then starts increasing to the top of the ozone layer. The top of this layer absorbs most of the ultraviolet radiation first, so the temperature is high there. It is also high at the earth's surface. In between, where

FIGURE 6–4
Temperature varies with height in the atmosphere.



the atmosphere is largely transparent to sunlight, the temperature is low.

The temperature changes at different heights mark different layers of the atmosphere. The **troposphere**, the layer next to the earth's surface, is warmed at the bottom. When air is heated from below, it rises. Ordinarily, before it reaches the top of the troposphere, it cools enough to stop rising and begins to fall. The air in the troposphere usually becomes thoroughly mixed by these rising and falling (convective) motions.

The **stratosphere**, above the troposphere, is warm at the top and cold at the bottom. It tends to be quite stable with little vertical air motion. The stratosphere acts like a lid on the unstable troposphere below. Relatively little water vapor gets into the higher layer, so the stratosphere plays only a small part in the water cycle.

About 30 per cent of the incoming solar energy is reflected to space. It is reflected mostly by clouds, but also by gas molecules in the atmosphere and by water, rock, soil, and vegetation at the earth's surface. Snow and ice are especially good reflectors of solar energy. If the earths' ice and snow surfaces increased, the earth would reflect more of the sun's beams. This would make the earth's average temperature fall.

Figure 6–3 shows the exchange of energy between the earth and space. Of 100 units of energy received from the sun, 30 units are reflected directly to space and are not used in heating the earth or its atmosphere. About 20 units are absorbed directly by the atmosphere, compared with 50 units absorbed directly by the earth's surface.

Because of the greenhouse effect, some of the heat from the earth's surface absorbed by the atmosphere is radiated back to earth. This exchange keeps the earth's surface much warmer than it would be without an atmosphere.

Thought and Discussion

1. Twice each day when the earth's surface is absorbing and emitting the same amount of energy, the temperature is constant for a brief period. Can you relate these temperatures to temperatures in the daily weather report?
2. What effect would a great increase in the atmosphere's water vapor have on the surface temperature? Would you expect more water vapor if the surface temperature were higher?

Solar Energy and the Earth's Climate

6–4 Insolation and the earth's temperature patterns

It is useful to have a contraction for incoming solar radiation, so the word **insolation** was made up. The amount of insolation has been measured at the earth's surface and by instruments on satellites. Each minute, at the outer

limit of the atmosphere a surface one centimeter square, *perpendicular to the sun's rays*, receives two calories of radiant energy from the sun.

The surface receiving the radiation has to be perpendicular to the sun's rays to get the full benefit of the sun's energy. Figure 6–5 shows why. Because the earth is round, most of its surface is not at right angles to the sun's rays. The higher the latitude, the more of the earth's surface the solar beam spreads over. Therefore, the amount of radiation on each unit area is less. Thus, insolation decreases from the equator to the poles. As a result, the equator is warm and the poles are cold.

On the average, the earth and its atmosphere emit to space all the energy absorbed. However, lower latitudes absorb more energy than they emit, and higher latitudes emit more than they absorb. (See Figure 6–6.)

The length of the period of daylight also controls the amount of solar energy received. The period of daylight, as well as the angle at which the sun's rays strike the earth, is related to the latitude and the season. For this reason, insolation is nearly constant along any given line of latitude.

As the earth moves around the sun on its tilted axis, the perpendicular beams of the sun move between 23½ degrees north and south latitude. Farther toward the poles the sun is never directly overhead. At the equator, and at the time of the equinoxes, the period of daylight is always 12 hours. The period of daylight increases toward the poles in summer and de-

Figure 6–5
Compare the relative amounts of energy received from the sun at points A, B, and C.

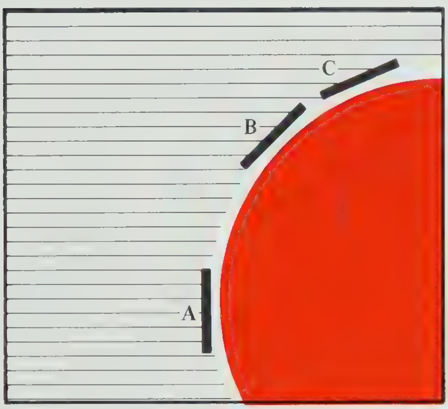
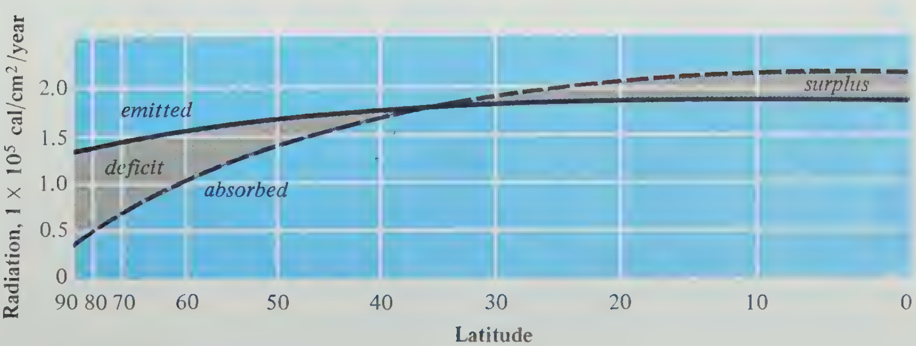


Figure 6–6
More radiation is emitted than absorbed at high latitudes (a deficit). More is absorbed than emitted at low latitudes (a surplus).



creases toward the poles in winter (Figure 6–7).

During the day the air absorbs energy, and its temperature rises, reaching a maximum shortly after noon. At night the atmosphere loses energy to space and cools off. With the longer days and more direct rays of sunlight in summer, heat accumulates from day to day. The average temperatures gradually rise. As winter approaches, more energy is lost at night than is received during the day. Average temperatures fall.

As the seasons change, the zone of maximum energy income shifts back and forth across the equator with the sun. (This zone moves farther than the sun's perpendicular rays because of the longer days of summer at high latitudes.) In the tropical zone the insolation doesn't change much from one season to another. There is always more incoming than outgoing energy. (See Figure 6–6.) The polar zones get little or no insolation in winter months and only small amounts in summer, so there is nearly always an energy deficit. In middle latitudes the incoming energy changes considerably during the course of the year.

Insolation is the most important factor controlling the earth's temperature patterns. (See Figures 6–8 and 6–9.) Yet if insolation alone

Figure 6–7
The length of daylight varies with latitude and the seasons.

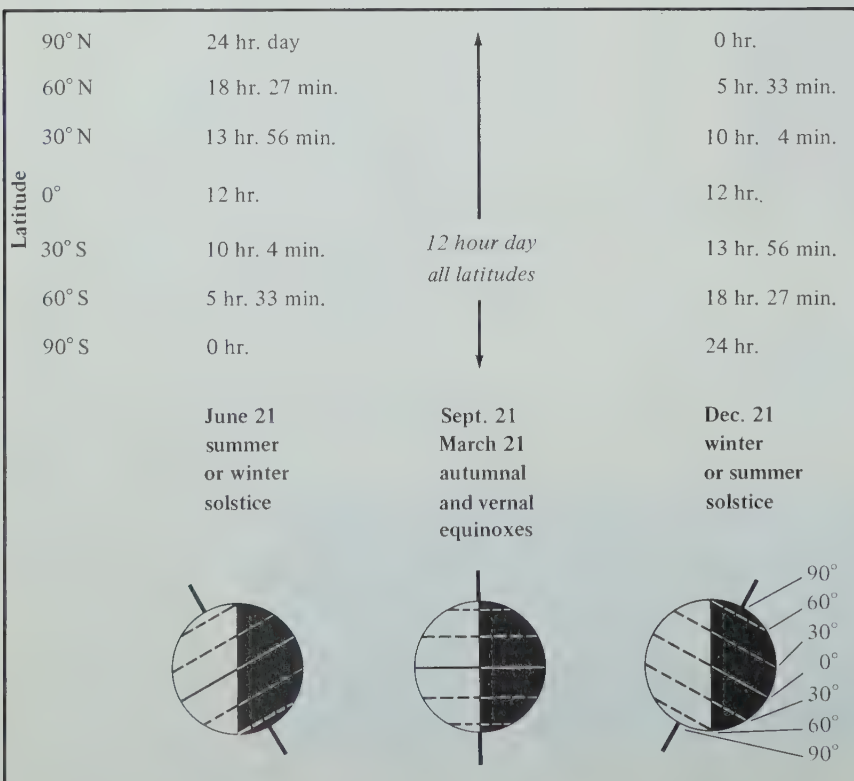


Figure 6–8
World map of average temperatures in July.

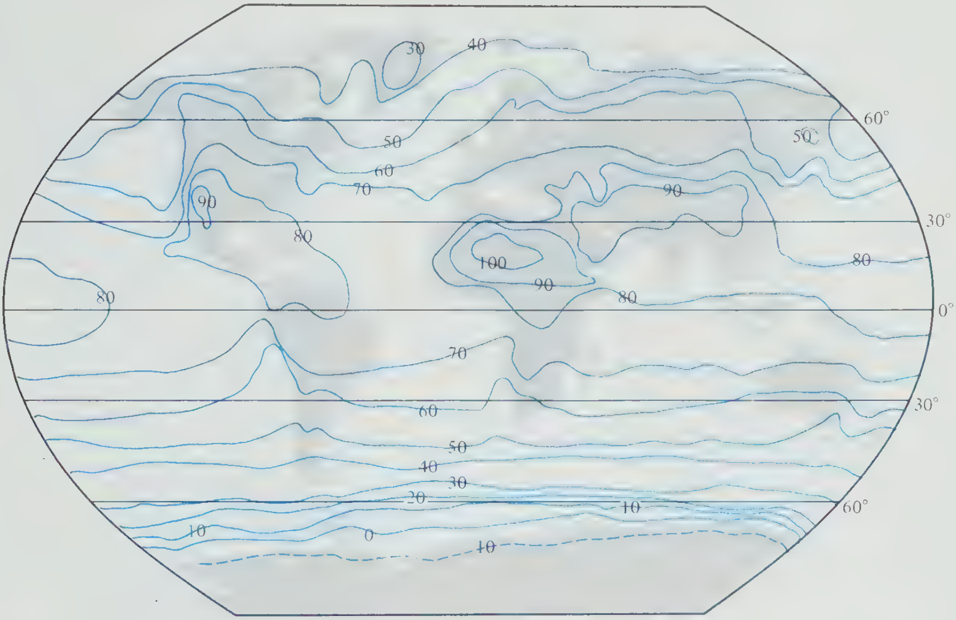
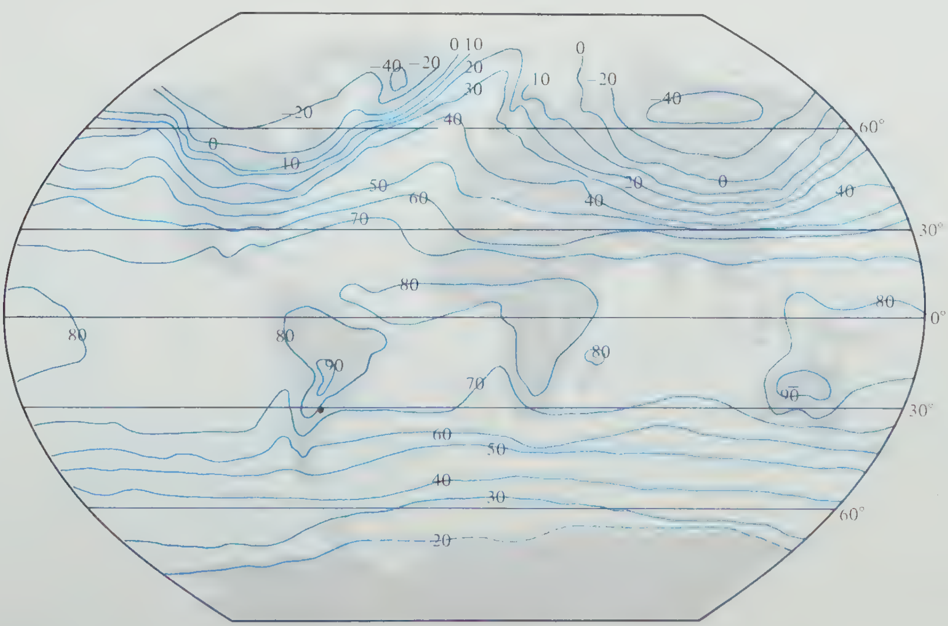


Figure 6–9
World map of average temperatures in January.



controlled the temperature, the **isotherms** (lines of equal temperature) on the world temperature maps would always be parallel to the circles of latitude. The isotherms are roughly parallel to the latitude circles. But there are places where they bend north and south. You will see why in the next investigation.

6–5 Investigating land and water temperatures

The island of Bermuda is both a winter and a summer resort. People from the United States can travel to Bermuda in the summer to escape the heat, and in the winter to escape the cold. After doing this investigation you will be able to explain why.

Procedure

Set up the materials as shown in Figure 6–10. Place a light 30 to 40 centimeters directly above the containers. Turn the light on and record the temperatures of the containers each minute for 10 minutes. After 10 minutes have passed, turn the light off and again record the temperatures each minute for 10 minutes.

Make a graph to summarize your observations. Plot the values for all four thermometers on the graph. Connect the plotted points for each thermometer with a smooth curve.

1. Does the air heat up faster over the soil or the water? Why?
2. Why were the rate of temperature change of the soil and the rate of temperature change of the water different?
3. Which received more heat energy from

FIGURE 6–10

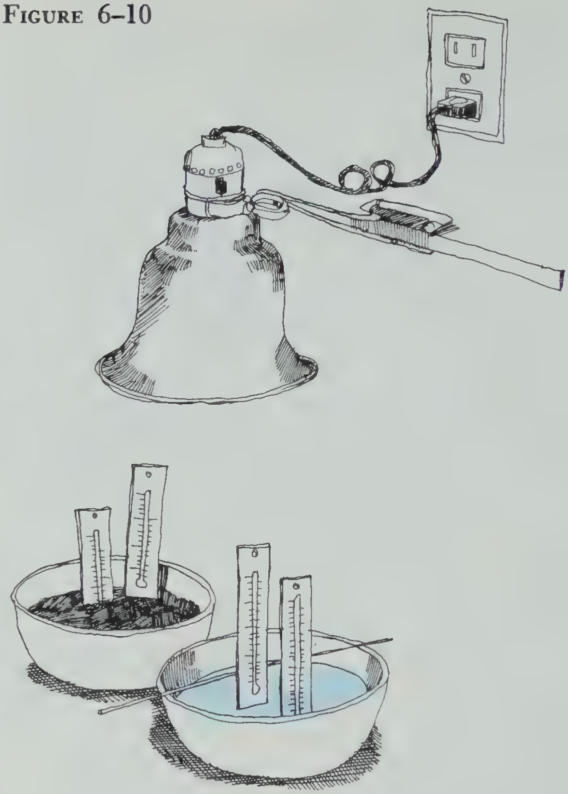
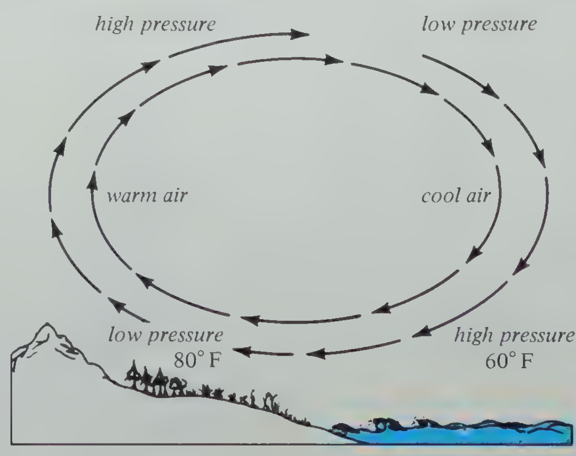


FIGURE 6–11

Unequal heating and cooling of land and water can cause seasonal monsoons and daily shore breezes.



the lamp, the soil or the water? Why?

4. *Which lost heat faster, the soil or the water?*
5. *The atmosphere gains heat from a* ***heat source*** *and loses heat to a* ***heat sink.*** *Which might be considered a heat source during the winter: soil or water?*
6. *Why do the isotherms in Figures 6–8 and 6–9 bend north and south?*
7. *How would you expect air pressure over a warm part of the earth's surface to compare with air pressure over a cooler area?*

Thought and Discussion

1. Because of the earth's round shape and its rotation, the insolation varies with latitude and is distributed equally around latitude circles. Do you think that the amount of energy absorbed is the same all around a latitude circle?
2. On the average, the low latitudes of the earth absorb more radiant energy than they emit. The high latitudes emit more energy than they absorb. The surplus heat at low latitudes must be transported to high latitudes to balance the earth's energy budget. Can you suggest two ways the energy can be transported?
3. Records show that the entire earth's average temperature is higher during the Northern Hemisphere summer when the earth is farthest from the sun than it is during the Northern Hemisphere winter when the earth is closest to the sun. Knowing that most of the earth's land masses are in the Northern Hemisphere, can you suggest why average temperature is higher when the earth is farther from the sun?

Energy and the Atmosphere's Circulation

6–6
Continents and oceans produce monsoons.

Investigation 6–5 showed how land and water affect the worldwide temperature patterns. The patterns reverse between summer and winter. The temperature differences between the land and the water also create wind patterns that change with the seasons.

In summer the continents heat up more than the oceans around them. The air over the continents is warmed by the underlying soil. The air becomes less dense and pushes upward. The surface pressure remains the same but pressure in the upper atmosphere increases. Higher pressure in the upper atmosphere forces the air to flow outward over the adjoining oceans. (See Figure 6–11.) This air flow increases the pressure over the ocean, pushing the surface air back to the continents.

During the winter, the ocean is warmer than the continents, so the circulation of air is reversed. These land-to-water and water-to-land circulations, changing their direction from winter to summer, are called **monsoons.**

The same kind of in-and-out flow of air occurs when the seacoast is heated during the day and cooled at night by radiation. When would you expect "onshore and offshore breezes"?

ACTION *Look at the world maps in Figures 6–12 and 6–13. These maps show the average sea-level air pressures and the average winds for July, when insolation is high in the Northern Hemisphere, and for January when insolation is low. Look especially at Asia, largest of all land masses. Explain the change in pressure and wind patterns from summer to winter in terms of land and water differences.*

Note that the maps do not appear like the daily weather maps. The moving lows and highs do not appear because they have been "averaged out" by combining many daily values.

6–7
The trade winds

In 1686 Edmund Halley published the first map of the winds of the world. Halley's map shows the broad belts of easterly **trade winds** that circle the globe on each side of the equator. The "trades" are remarkable because they show only slight changes in direction and speed from day to day. They are by far the steadiest winds in the lower atmosphere, and they cover a good portion of the globe.

Halley pieced his map together from captain's logs. To the sailors of that day, the steady trades promised a reasonably sure trading voyage to the New World. To Halley, the uniform, broad belt of the trade winds suggested an orderly circulation of air, caused by the uneven heating of the earth's surface. Halley explained the monsoons in the same way—that is, by convection resulting from unequal heating of the earth's surface.

He suggested that the trades are caused by the rising of heated air near the equator, where the sun's heat is greatest. The rising air is replaced by air from the trades, blowing from the cooler regions of the earth. However, Halley's theory did not satisfactorily explain the direction of the trade winds. The trades do not blow directly along the meridians. One would expect them to if changes in insolation at different

FIGURE 6–12
Sea-level pressure and wind patterns near the earth's surface in January.

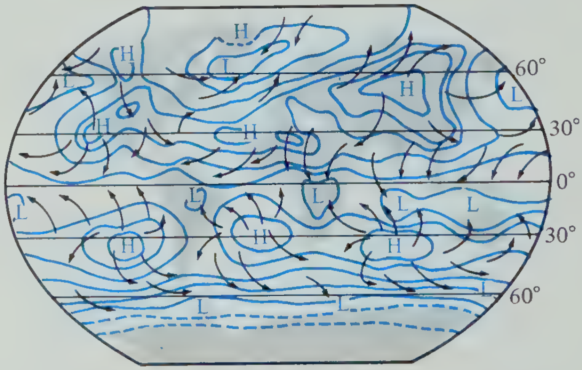
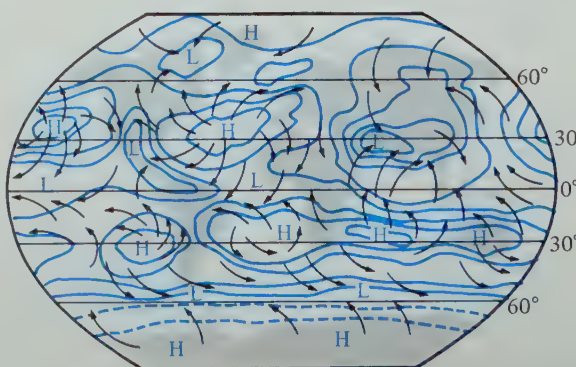


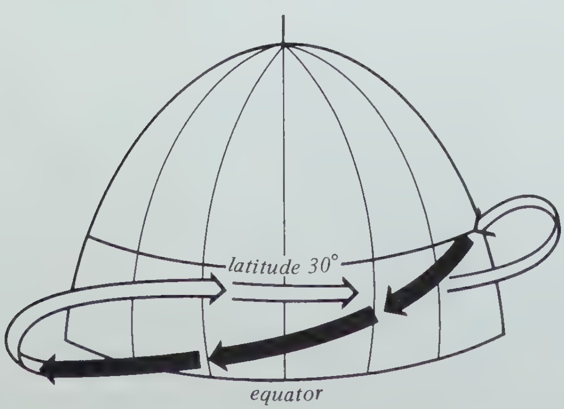
FIGURE 6–13
Sea-level pressure and wind patterns near the earth's surface in July.



latitudes were the only factor. Instead, the trades blow from the northeast in the Northern Hemisphere and from the southeast in the Southern Hemisphere.

Fifty years later, George Hadley showed why the trades are easterly winds. He accepted Halley's idea of a large convective cell in each hemisphere. Heated air rises at the equator, moves poleward, and cools and sinks at high latitudes. However, he said, in moving along the meridians the air gains or loses eastward speed relative to the earth. You know this phenomenon as the Coriolis effect. (Hadley worked out this part of it 100 years before Gaspard de Coriolis.) Air moving toward the equator loses speed relative to the earth below. Thus the air sinking and returning toward the equator finally develops into the northeast and southeast trade winds. (See Figure 6–14.)

FIGURE 6–14
The Coriolis effect influences the direction of winds. Air rising at the equator and flowing toward the North Pole becomes a westerly wind. Air sinking near latitude 30° flows back toward the equator from the east.



ACTION *Meteorologists have been able to calculate the average wind velocity at each latitude all around the earth in the troposphere and stratosphere. They find that the average speed along the latitude circles is great, but the average drift along the meridians is small. To understand how air can gain speed toward the east or west as it drifts along the meridians, you can make some simple calculations.*

A point on the equator moves eastward at a speed of 25,000 miles a day. At the latitude of New Orleans, the eastward speed due to the earth's rotation is 21,675 miles a day. Imagine that air moves from the equator to New Orleans. Assume, too, that the air keeps its original eastward velocity as it moves north. What will be its eastward motion, relative to the earth, when it reaches the latitude of New Orleans? (You can use the Coriolis Effect Kit to help you visualize what's happening.)

Friction and pressure forces in the atmosphere slow the wind's speed. Nevertheless, westerly winds in the high troposphere often reach speeds greater than 100 miles an hour.

What would be the westward speed of air, originally at rest at New Orleans, if it were moved to the equator? Assume the air is not slowed down by friction or pressure forces.

Hadley explained the easterly trade winds, but he pointed out that the winds could not blow from the east everywhere over the earth's surface. Their friction would slow down the earth's rotation. The easterly trades thus have to be balanced by winds from the west—the

"brave westerly winds" that sailors found at middle latitudes. Hadley explained the westerlies by pointing out that air moving poleward at high levels would gain relative motion and seem to be blowing from the west. This air, sinking to the earth's surface at high latitudes, would form the westerlies. (Hadley thought the westerlies drift toward the equator, but in reality they drift toward the poles.)

At the conclusion of his short paper on the atmosphere's "general circulation," Hadley wrote, "Thus I think the NE winds on this side of the equator, and the SE on the other side, are fully accounted for."

6–8
World patterns of pressure and wind

Until organized weather observations were made, there was no way of observing the moving eddies, the lows and highs that you are following in your Weather Watch. Early scientists were not aware of them. Hadley attempted to explain what he called the **general circulation** of the atmosphere from maps of the average winds at the earth's surface. The term general circulation is still used to describe an orderly pattern of global air motion underlying the changing patterns of the winds.

Today, meteorologists are not as confident as Hadley was that they have "fully accounted for" the easterlies and westerlies. The circulation is much more complex than he imagined it to be. Hadley believed that the atmosphere's motion along the meridians could be represented by one large convective cell in each hemisphere. Instead, there seem to be three cells between the equator and the pole of each hemisphere. One cell is in the tropics, one in each polar region, and one at middle latitudes. A simple picture of the average motions that fits present observation and theory is shown in Figure 6–15.

According to present theory, the three-celled form of circulation may be traced to two factors. The most important factor is the earth's rotation speed. The other factor is the difference in temperature between the equator and the pole. Scientists are testing these theoretical conclusions by experimenting with models of the earth's atmosphere.

In these experiments, the rate of rotation and the temperature difference between the equator and the pole can be changed. When the values of rotation and temperature difference corresponding to those of the earth are used, the motions form patterns like those on the daily weather map and like those in Figure 6–15. The patterns of motion in the models change continually, like those in the atmosphere. Continual change is a built-in feature of the earth's atmosphere. Figure 6–15 indicates the average patterns of flow in the earth's troposphere.

Some of the air that rises at the equator and moves poleward sinks to the earth's surface near latitude 30 degrees. Part of this sinking air flows back toward the equator as the trade winds. Near the equator, the air rises and makes another circuit. The trade winds are thus part of a larger circulation of air. This circulation is still known as the Hadley cell. The trades of the two hemispheres flow together, or con-

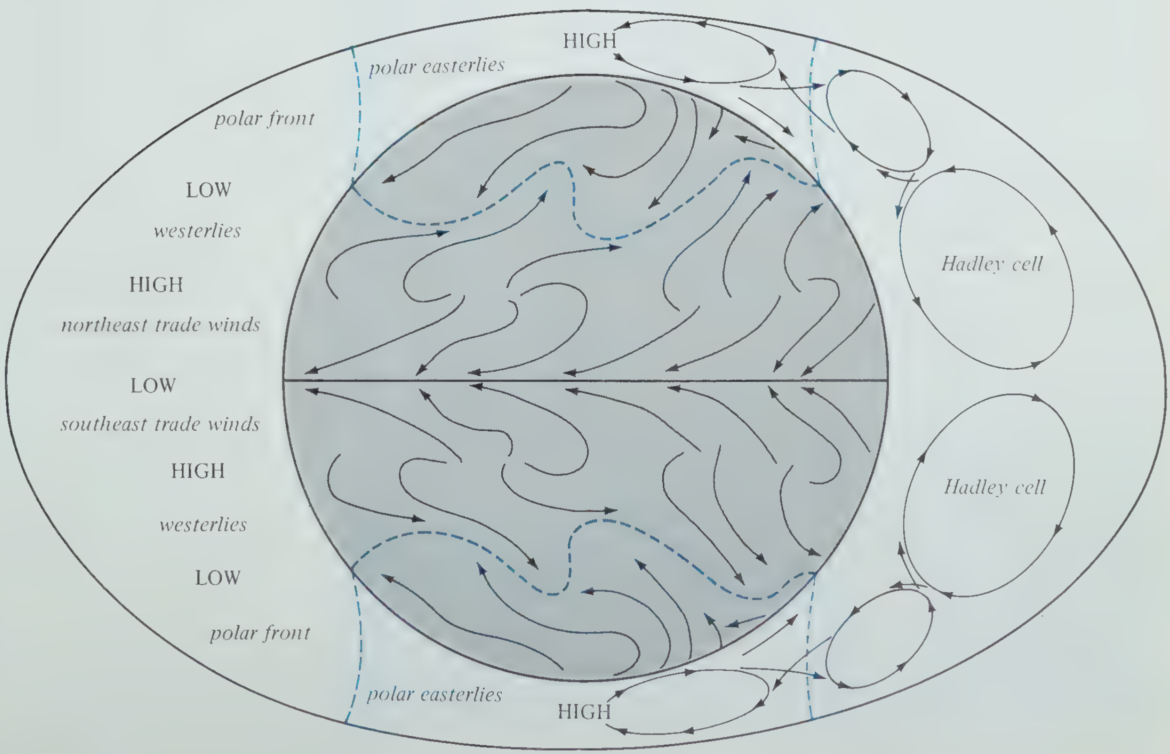
verge, near the equator in a region of calms. The mariners of Hadley's day called this region "the doldrums." (Today it is known as the Intertropical Convergence Zone.)

Over each of the polar regions, where there is little or no solar radiation most of the year, the air cools and sinks. It forms a shallow high-pressure area at the earth's surface from which air flows toward the equator. This cold air is deflected by the earth's rotation and becomes the belt of the polar easterlies. (See Figure 6–15.) The polar easterlies occupy a thin layer of air next to the earth's surface.

Part of the upper level air that sinks into the high pressure cells at latitude 30 degrees drifts toward the poles. This current becomes the prevailing westerly current of middle latitudes. Drifting poleward, the warm air of the tropics is brought next to the cold air of the polar easterlies. A zone of great temperature contrast results. Large horizontal eddies develop in this zone.

As you will learn in Chapter 7, these eddies are the traveling lows and highs of the daily weather map. The eddies in the westerlies transport heat to colder latitudes. They also help

Figure 6–15
Simplified wind belts and pressure belts. Where winds converge, is the pressure high or low? Where winds diverge, what is the pressure?



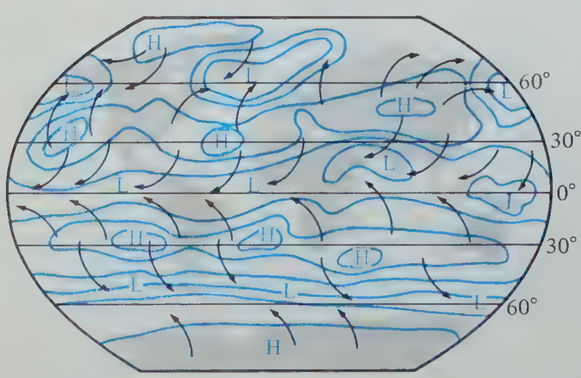
maintain a balance between easterly and westerly winds at the earth's surface. Thus the traveling lows and highs have to be included in any complete picture of the general circulation.

Look at Figure 6–16 to see if you can identify the trade winds, the westerlies, and the polar easterlies. Compare the observed map of pressure and wind with the idealized model of the general circulation in Figure 6–15. Sinking air at latitude 30 degrees and over the poles keeps the sea-level pressure high in these regions. Where the motion is upward, the sea-level pressure is low.

Now look at the view of the Northern Hemisphere that is shown in Figure 6–17. Do the cloudy areas on a single day reflect the main features of the general circulation? The broad, nearly continuous band of clouds near the equator marks the Intertropical Convergence Zone. Here the trade winds of the two hemispheres converge. As the air converges, it has to rise. The upward motion produces many large cumuliform clouds. Like giant explosions, these big clouds send vast quantities of latent heat into the atmosphere where it is released by condensation. In this way the water cycle supplies much of the energy that drives the Hadley cell and the atmosphere's circulation. You may also be able to find on the map clouds produced by monsoons.

In Chapter 7 you will discover the important part the traveling eddies of the general circulation also play in the water cycle. These, too, you can identify in the view of earth from space. The most common type occurs where warm and cold air meet at middle latitudes. But large traveling eddies also occur in the tropics.

FIGURE 6–16
Average annual sea-level pressure and generalized wind patterns near the earth's surface.



Thought and Discussion

1. When air currents near the earth's surface meet or *converge*, what happens to the air? When air currents flow out of a region or *diverge*, where does the air come from?
2. What causes motion in the atmosphere along the latitude circles?

Unsolved Problems

To accurately predict the atmosphere's motions is one of the unsolved problems of earth science. You have learned that the atmosphere's motions can be explained, in a very general way, by several factors. The basic factor is the way solar energy is distributed over the earth. The composition of the atmosphere and the earth's surface affect the way the sun's energy heats the atmosphere and sets it in motion.

The earth's round shape and its spinning motion strongly influence the air's motions.

In recent years, meteorologists have made much progress in forecasting the large-scale motions of the atmosphere. Big computers have made it possible to solve the equations that describe the motions. However, many difficulties prevent highly accurate predictions. One difficulty is that only a small portion of the atmosphere is observed in the detail necessary. During the 1970's under the United Nations' Global Atmospheric Research Program, scientists will get many more observations from all over the world. With these, they will learn more about the atmosphere and try to make longer-range and more accurate predictions.

The lack of observations, however, is only one of the problems that must be solved. There are many other reasons why the air's motions cannot be predicted accurately. For example, water in the air with its phase changes from vapor to liquid or ice and back again introduces complexities. Condensation releases energy, and clouds affect the incoming and outgoing radiation.

To make accurate predictions, one must know not only what is going on within the atmosphere, but also what takes place at its boundaries. The atmosphere is strongly coupled with another fluid at its base: the ocean. The

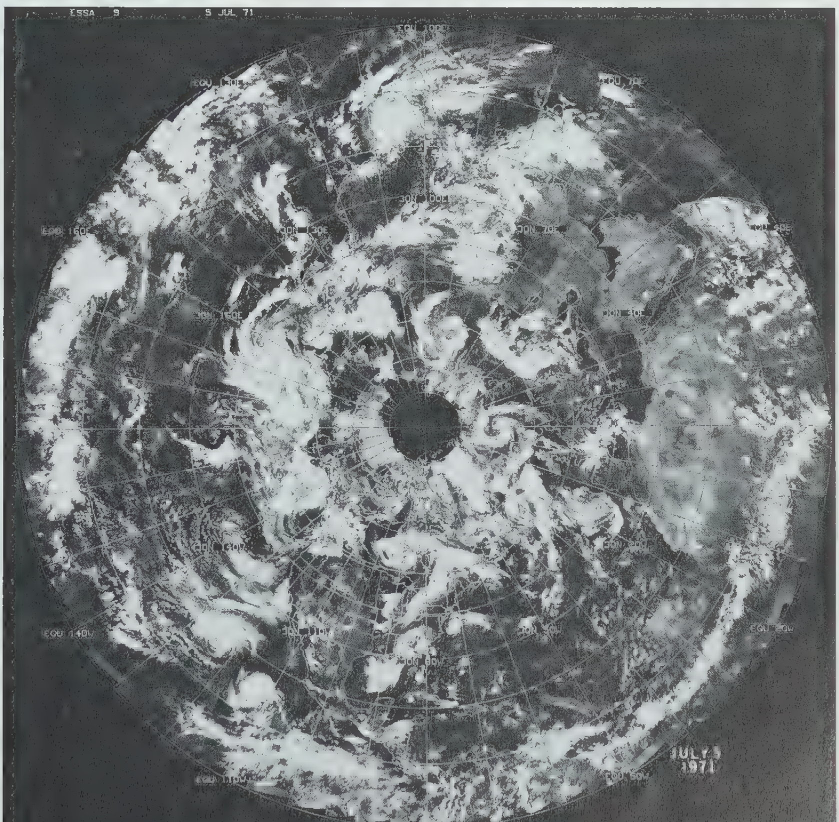


Figure 6–17
Cloud patterns in the Northern Hemisphere as viewed from a weather satellite.

ways the ocean affects the atmosphere, and vice versa, are far from being completely understood. Very little is known about the connections between the upper and lower atmosphere. Variations in the sun's surface cause marked changes in the upper atmosphere, but meteorologists do not know to what extent these changes influence the motions lower down.

Finally, scientists do not yet fully understand how the small-scale and larger-scale motions of the atmosphere are interrelated.

Chapter Review

Summary

Energy from the sun produces the circulation of air and water in the atmosphere. The earth is in radiative balance, emitting the same amount of radiation it absorbs from the sun. The earth's temperature range, determined largely by its distance from the sun, allows water to occur in all three states and thus to move through the water cycle.

The earth and its atmosphere absorb about 70 per cent of the insolation. The rest is reflected to space by clouds, air molecules, ice and snow, and other materials at the earth's surface. The atmosphere absorbs only a little of the incoming energy; the earth's surface absorbs far more. The earth's surface emits long-wave radiation, most of which is absorbed by water vapor and carbon dioxide in the atmosphere. These gases radiate energy downward as well as upward, so that the earth's surface receives energy from the atmosphere as well as the sun. As a result, the earth's surface is warmer than the atmosphere above; it is much warmer than it would be if there were no atmosphere to trap the energy.

The earth's roundness causes the incoming energy to be unevenly distributed between the equator and the poles. This distribution produces an energy source at the equator and energy sinks at the poles. The higher latitudes emit more energy than they absorb, whereas the lower latitudes absorb more energy than they emit.

The latitudinal distribution of radiation largely controls the earth's temperatures. But land and water strongly influence the temperature and its seasonal and daily variations. Land heats more rapidly than water. The temperature of soil or rock increases much more than water temperature when a given quantity of heat is absorbed. Moreover, energy does not penetrate deeply into the soil or rock. In water, heat may be carried downward by the water's motions. For the same reasons, the land also cools more rapidly than the oceans. Energy is also used to evaporate water, resulting in the more even temperature of the oceans.

The unequal heating of land and water leads to unequal heating of the atmosphere. This results in unbalanced pressure forces that drive the air from high to low pressure areas. Thus, the land and water contrasts produce seasonal circulations called monsoons.

If the earth did not rotate, air might rise at

the equator, flow to the poles, sink, and then return to the equator near the earth's surface. However, the earth's rotation causes the air currents to be deflected so that they tend to flow parallel to the latitude circles instead of directly across them.

The poleward moving currents that do exist leave the equator, sink near latitude 30 degrees, and create the subtropical high pressure belts. One branch of the sinking currents turns equatorward as the trade winds. The other branch turns poleward as the westerlies of middle latitudes. The westerlies bring warm air from the tropics next to the cold air of the polar easterlies. Horizontal eddies form and transfer heat from the low to the high latitudes.

The motion patterns in the atmosphere exist on many scales. They are necessary links in the water cycle and depend in part for their development on energy released during the cycle.

Questions and Problems

A

1. If an object is radiating the same amount of energy it is absorbing, does its surface temperature rise, fall, or remain the same?
2. If the earth were twice its present distance from the sun, what would be its approximate temperature?
3. How do water vapor and carbon dioxide keep the earth's surface warm?
4. If a pan containing water is heated at the rim and cooled at the center, what motion takes place?
5. What is a monsoon?

B

1. Show how temperature differences produce horizontal pressure differences in a fluid?
2. Where on earth would you expect to find the greatest annual range of temperatures?

C

1. Explain how the dimensions of the atmosphere are related to the air's patterns of motion, namely, vertical cells and horizontal eddies.
2. When the air is very dry, the temperature just before sunrise tends to be lower than when the air contains a lot of water vapor. Can you explain why?

Suggested Readings

Craig, Richard A., *The Edge of Space, Exploring the Upper Atmosphere*. Anchor Books, Doubleday and Company, Inc., Garden City, New York, 1968. (Paperback)

Edinger, James G., *Watching for the Wind, The Seen and Unseen Influences on Local Weather*. Anchor Books, Doubleday & Company, Inc., Garden City, New York, 1967.

Harris, Miles F., *Man Against Storm: The Challenge of Weather*. Coward-McCann, Inc., New York, 1962, Chapters 1 and 2.

Ohring, George, *Weather On the Planets: What We Know About Their Atmospheres*. Anchor Books, Doubleday & Company, Inc., Garden City, New York, 1966. (Paperback)

Thompson, Philip D., O'Brien, Robert, and the editors of *Life*, *Weather*. Time, Inc. (Life Science Library), New York, 1965.

7. Wind, Weather, and Climate

Geologists are able to picture the earth's climate and its changes far back in time. During the past half-billion years, the average temperature has been alternately warm (about 68°F) and cold (about 54°F). The cold periods have been relatively short; they are the exception rather than the rule. For most of the half-billion year period, the climate was milder than it is now.

The earth is still emerging from the latest and best-known cold period, the Quaternary Ice Age. At least four times during the Quaternary, great sheets of inland ice, thousands of feet thick, spread from cold regions out over the plains. There was more floating ice in the ocean than now. So much water was frozen during these glacial periods that sea level was lowered by about 100 meters. Places outside the ice-covered areas probably received much more rain than they do now. Regions that are now dry and arid once supported large populations.

By 1970 obvious changes in the weather and climate of the earth's cities began to attract wide notice. More and more heat, water vapor, and other gases, as well as solid particles, were being put into the atmosphere. Could man's activities eventually cause the climate to swing back into a wet glacial period, or into a dry, milder period when the polar ice caps would melt and the sea level rise?

Basically, the earth's climate depends on the amount of energy it receives from the sun and on the way energy and moisture are distributed. This chapter will explore the many factors that influence the distribution of energy and moisture at the earth's surface and in the atmosphere.

Weather and the Water Cycle

7–1
Investigating the weather—Weather Watch

In your Weather Watch you have made daily observations of the most important weather elements and plotted each day's observations on a graph. Perhaps you have wondered about the weather changes shown on your graph and tried to predict the weather for the next day.

Since you began the Weather Watch, you have learned more about the way solar radiation, air motion, and moisture control the weather. Now you may be able to form some hypotheses about how these factors interact to influence the weather.

Procedure

Study the wall graph made from your observations in the Weather Watch. See if you can discover relations between the following weather elements:

1. ***Wind direction** and changes in **pressure.***
2. *Change of **temperature** and changes in **pressure.***
3. ***Cloudiness** and changes in **pressure.***
4. ***Precipitation** and changes in **pressure.***

Select one week in which you can see a definite change in your local weather. Compare your graph for that week with the Daily

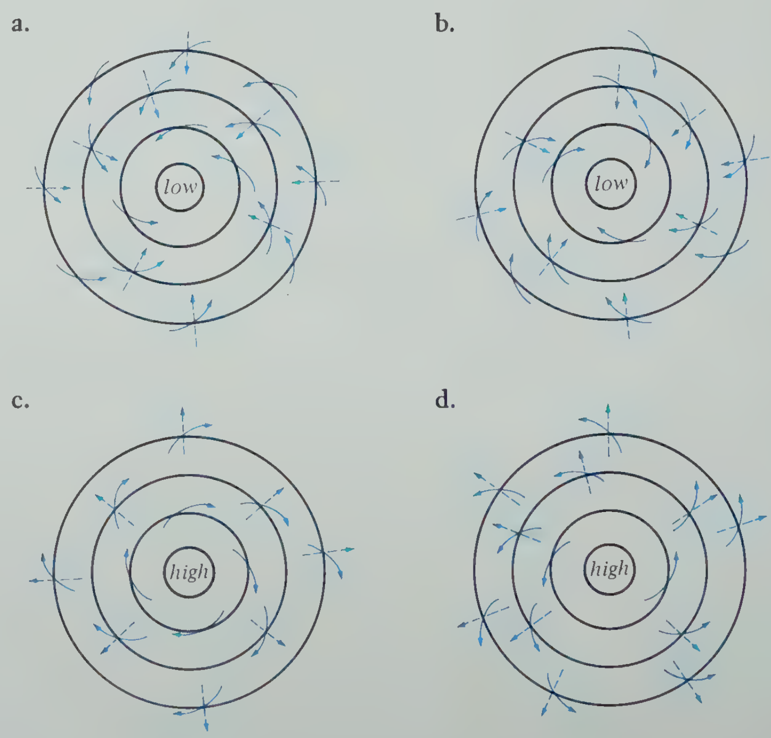


FIGURE 7–1
a. *Cyclonic circulation in the Northern Hemisphere.*
b. *Cyclonic circulation in the Southern Hemisphere.*
c. *Anticyclonic circulation in the Northern Hemisphere.*
d. *Anticyclonic circulation in the Southern Hemisphere.*

Weather Map of the United States for the same period. Observe the region around your locality, too.

5. *Explain how the local weather changes fit into the broad pattern of weather moving across the continent.*

7–2
Cyclones and anticyclones

In Investigation 7–1, you discovered that weather is related to the passage of moving low and high pressure areas. In the Northern Hemisphere, the wind spirals into and around the center of a low pressure area in a counterclockwise direction. This pattern of air motion forms a **cyclone** that can be hundreds of miles in diameter. In an **anticyclone** the wind spirals outward from a high pressure center, and around it, in a clockwise motion. In the Southern Hemisphere the direction of rotation is reversed. (See Figure 7–1.)

Most strong winds, clouds, and precipitation occur in cyclones. Anticyclones usually bring clear skies and fair weather. Anticyclones and large cyclones often occur in pairs.

Westerly winds control the development of cyclones and anticyclones. The velocity of the westerly winds increases rapidly with altitude. Several miles above the earth's surface the westerlies flow in a meandering stream or wave around the pole of each hemisphere. (See Figure 7–2.) The snakelike wave usually moves from west to east. At 30,000 feet the center of

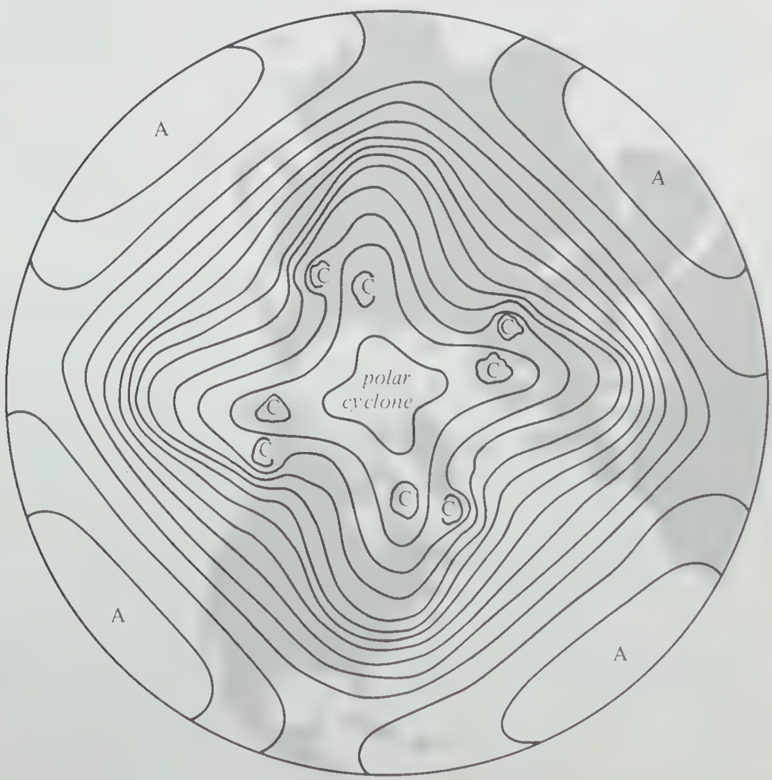


FIGURE 7–2
The westerly winds seen from above the North Pole.

the westerly stream moves fast enough to slow down or speed up a jet plane by as much as 200 miles per hour. This strong core of the westerlies is called a **jet stream.**

In the lower atmosphere, cyclones and anticyclones develop under the waves in the strong westerly stream. Figure 7–3 shows how a cyclone and an anticyclone form under a wave in the westerlies. At point C the air aloft moves through the wave faster than it is replaced. This causes a drop in pressure near the earth's surface, and a cyclone begins to form. At point A the upper winds flow inward or converge. The air accumulates and the pressure rises at the earth's surface. An anticyclone begins to form. The air in a cyclone moves upward while the air in the anticyclone sinks.

7–3
Warm and cold fronts

Action *With a rectangular container such as a plastic tank or a glass baking dish you can make a model of the boundary between fluid masses. Fill the container with water and make a plastic or cardboard wall to divide the tank into two parts. (See Figure 7–4.) Pour salt into one half of the tank and then add food coloring to the same side. Allow the water in the tank to become calm. Which water mass is denser? Which could represent a cold air mass? Carefully draw up the separating wall. Try not to disturb the water. Describe what happens in the tank.*

Figure 7–3
Cyclones and anticyclones form under waves in the westerlies.

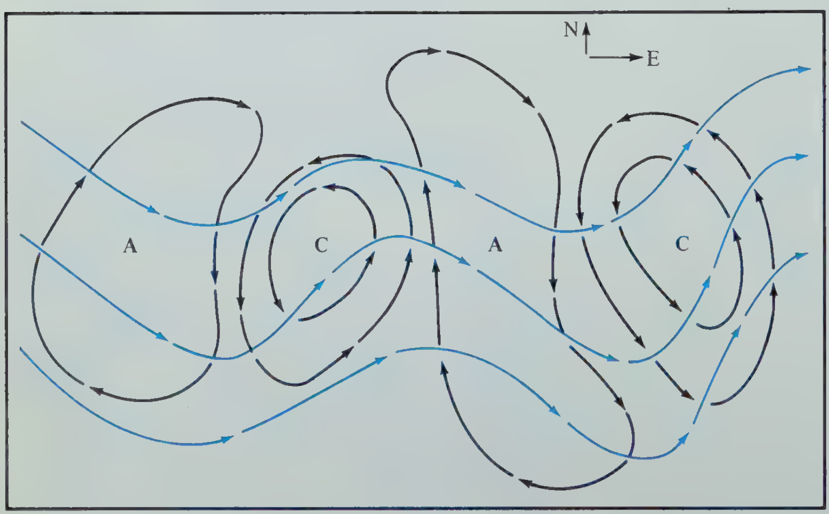
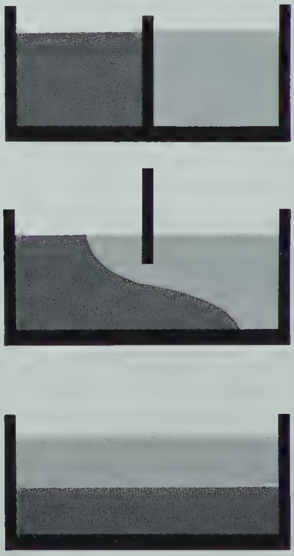
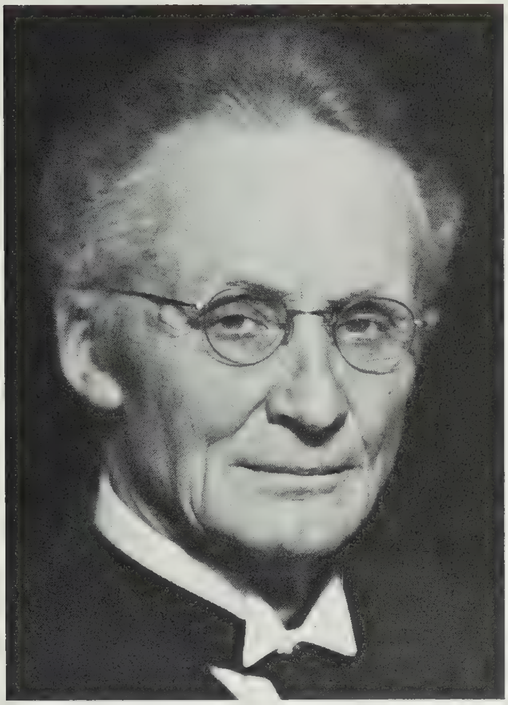


Figure 7–4
A front forms between two water masses of different densities. Is a front an interface?



VILHELM BJERKNES



By 1912 Vilhelm Bjerknes (1862–1951), a Norwegian physicist, had become recognized as the founder of modern **physical hydrodynamics,** the study of forces and motion in fluids. In that year, on being named Director of the Geophysical Institute at the University of Leipzig, Bjerknes announced a new goal. He would consider his task done, he said, if in one year he could correctly calculate the change of weather during one day. "It may take a year to dig a tunnel through a mountain," he pointed out, "but, later, others may make the passage with an express train."

In 1917 Bjerknes returned to Norway to establish a geophysical institute at Bergen. There, with his son, J. Bjerknes, and Halvor Solberg he laid the basis for a revolution in weather forecasting. During World War I, Norway was cut off almost completely from weather reports outside Scandinavia. Bjerknes was successful in establishing a network of weather observing stations located close together along the Norwegian coast.

His plan was to analyze the reports from this small network of stations intensively, applying his theories of fluid motion. Other young Scandinavian scientists joined the Bergen group. They would work enthusiastically far into the night, when V. Bjerknes might look into the map-room with his eyes gleaming and ask: "Are there any new discoveries tonight?"

In the Action, a **front** forms between two water masses of different densities. (A front is the boundary between two fluid masses.) Because the dense mass slides under the lighter mass, the front becomes inclined. If enough time is allowed, the front in the tank will become horizontal.

The boundary separating the warm westerlies from the cold polar easterlies is called the **polar front.** Because of the earth's rotation, the cold, dense air remains inclined like a sloping wedge under the warm air. (Notice in Figure 6–15 that the polar front slopes upward toward the pole.)

As cyclones develop, the polar front is distorted as shown in Figure 7–5. The cyclone develops in stages. The warm air of the westerly winds is pushed against the cold air. The warm air glides up and over the cold air, forming a warm front. The cold air to the north swings around and pushes the warm air southward. That part of the cyclone is called the cold front. At the same time the whole cyclone moves eastward in the same direction as the strong winds high in the troposphere.

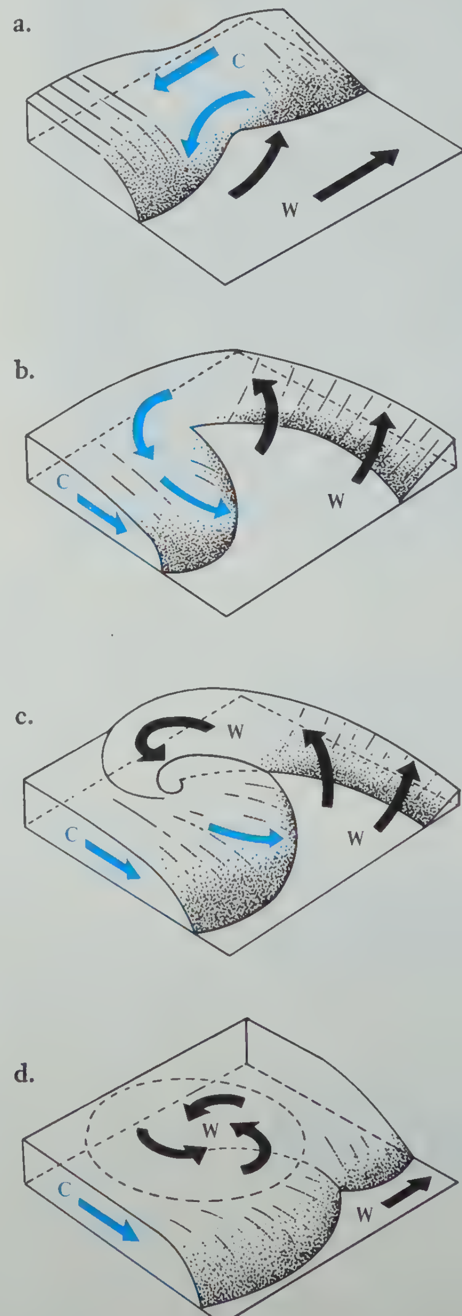
Since the cold air moves faster than the warm air, the area of warm air, called the warm sector, narrows. (See Figure 7–5c.) The cold dense air sinks and spreads out, forcing the less dense air upward. As the cold air near the center of the cyclone overtakes the warm front, all of the warm air between the two fronts is squeezed upward (Figure 7–5d). The squeezing of the warm air upward is called **occlusion.** When the warm sector has disappeared, the air masses are stable and no new winds are created. At this stage the cyclone begins to decay because friction with the earth's surface gradually slows the motion of the winds.

A cyclone moves most rapidly when it is first developing. A mature cyclone moves less rapidly, and an occluded cyclone nearly stops its forward motion.

7–4
Air motions and weather

Because the atmosphere has a circumference about 1,250 times its height, the large-scale motions of the atmosphere are nearly horizontal. For example, the motions within a polar-front

Figure 7–5
Stages in the development of a cyclone.
a. *At the polar front, warm air and cold air push against each other.*
b. *A warm front and a cold front form.*
c. *The warm air is occluded.*
d. *The cyclone begins to decay.*



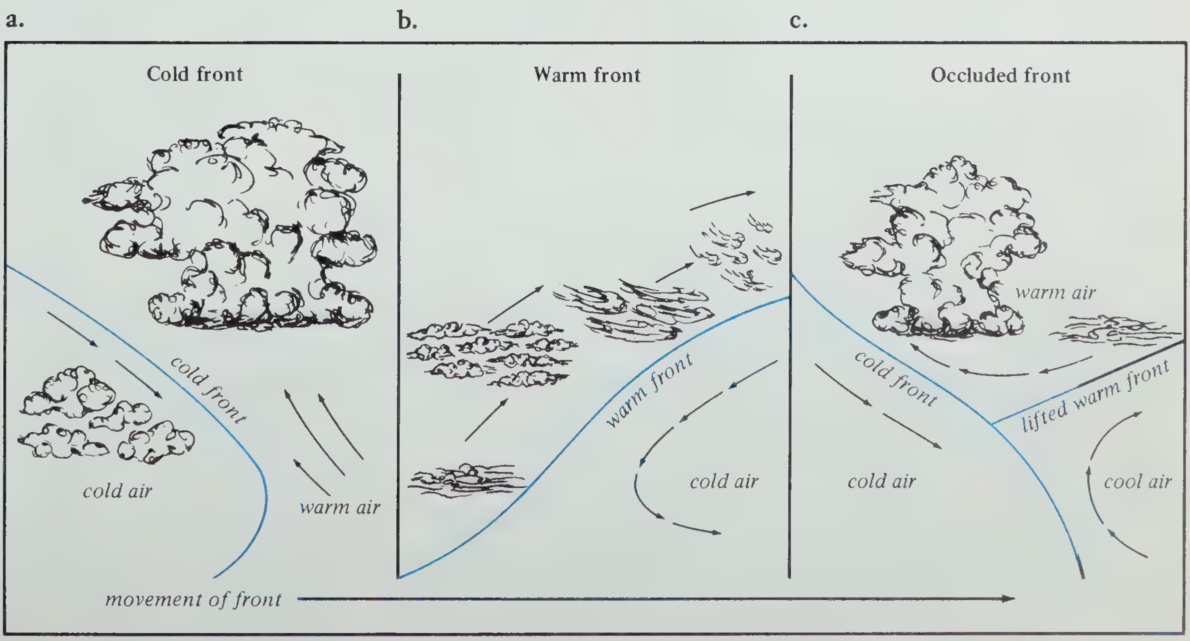
cyclone take place in a very thin disc of moving air no more than 5 or 6 miles thick but often 1,500 miles in diameter.

As a large cyclone develops along the polar front, the westerlies dip into the subtropics, capturing warm, moist air. The cyclone and warm air are carried poleward while an anticyclone, carrying cold air, is swept toward the equator.

Since the atmosphere never develops a steady motion, the weather changes from day to day. When there is a large temperature difference between moving masses of air, bad weather will normally result. The warm front has a gentle slope. (See Figure 7–6.) The motion of the warm, moist air is gradual and widespread. This motion usually produces stratiform clouds and steady rain or snow. Advancing cold air often lifts the warm air abruptly. The warm air mass frequently becomes unstable. Cumuliform clouds, showers, and sometimes thunderstorms result.

In addition to cyclones and anticyclones, there are other motion patterns in the atmosphere that are shaped like whirls or eddies. Some have clouds and precipitation and some do not. Sensitive instruments show that the wind contains eddies only a few centimeters in diameter. These whirls usually carry heat and water vapor upward into the atmosphere. Larger eddies are felt by passengers on an airliner as turbulent air near the earth's surface.

Figure 7–6
The typical weather with:
a. *a cold front*
b. *a warm front*
c. *an occluded front*



Still larger eddies are noticeable when an airliner comes down through cumulus clouds. The turbulence is caused by upward and downward currents in the cloud cell.

7–5 Thunderstorms

Thunderstorms are about as tall as they are broad. The vertical motions of these convection patterns are of about the same size as the horizontal motions. When the air is very moist and unstable, cumulus clouds develop into huge, towering clouds called **cumulonimbus.** (See Figure 7–7.) These clouds are accompanied by lightning and thunder. Cumulonimbus clouds are wider and taller than ordinary cumulus clouds. Severe storms can contain several vertical cells and reach 30 miles in diameter.

Thunderstorms get much of their energy from the large quantities of latent heat released during condensation. This heat keeps the rising air warmer than the surrounding air. In this way, the most intense thunder clouds can reach heights of 15 kilometers (50,000 feet). They may occasionally penetrate the stratosphere.

There are two types of thunderstorms. Local thunderstorms are caused by surface heating of an unstable air mass on a hot day. More intense storms are created by larger-scale air motions. When the winds bring dry, cold air above warm, moist air, thunderstorms often develop in a **squall line** hundreds of miles long. In a squall line, the forward motion of the storms helps to prolong them. Rain from the thunderstorm evaporates as it falls, cooling the air. The cold air descends, moving in the direction of the storm, and forces the warm, moist air ahead of the storm upward. The moisture in the warm air condenses and more energy is released. (See Figure 7–8.)

Lightning is a sudden discharge of electricity between parts of a cloud or between a cloud and the ground. The charges on water drops or droplets become separated by their up and down motions in a thunderstorm. Parts of the cloud become positively or negatively charged. When the discharge or spark occurs, a channel of air perhaps 10 centimeters in diameter can be heated to about 15,000°C for a few ten-millionths of a second. The heated air expands explosively, causing the sound of thunder.

Light travels faster than sound. You can use this fact to estimate your distance from a thunderstorm. Count the number of seconds between the flash of lightning and the clap of thunder. Divide by five to find the number of miles away the lightning struck.

If you are on a high, exposed place when a thunderstorm strikes, move quickly to the lowest spot in the area. Don't seek "shelter" under the lone tree in a field. You and the tree might become lightning rods!

7–6 Tornadoes and hurricanes

Tornadoes also occur in squall lines. They are most frequent over the midwestern and eastern United States in spring and summer. **Tornadoes** are small rotating storms several hundred meters

Figure 7–7
A large cumulonimbus cloud, known as a thunderhead.

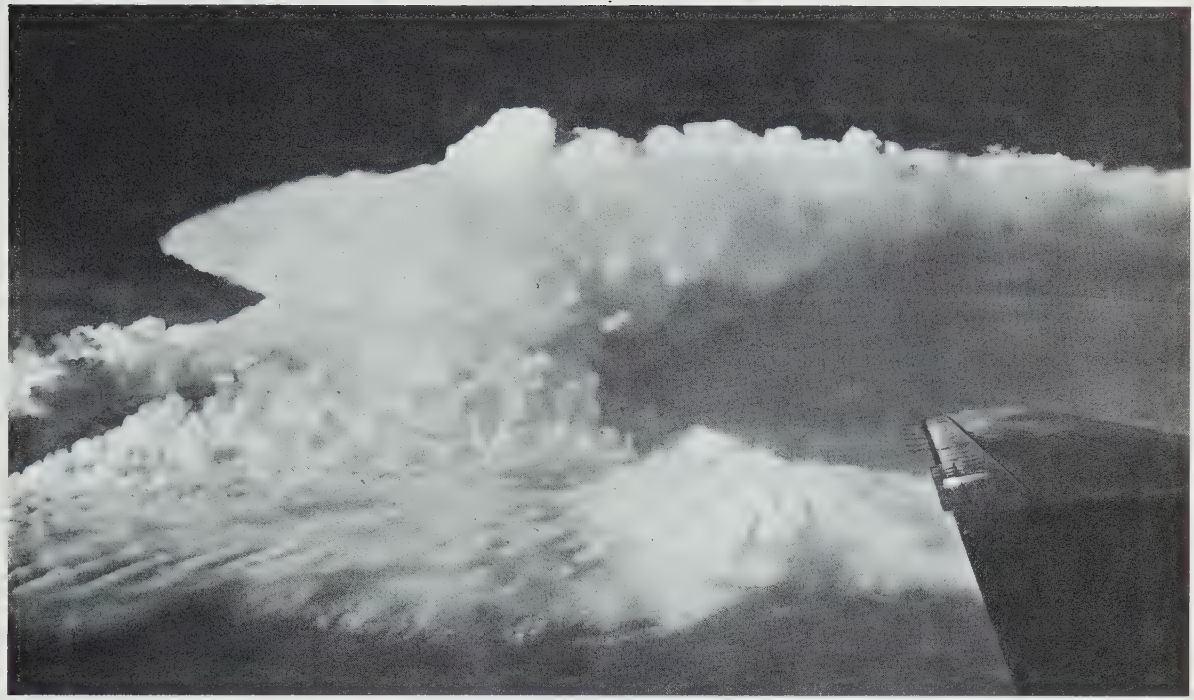


Figure 7–8
The air motions in a large thunderstorm moving in a squall line.

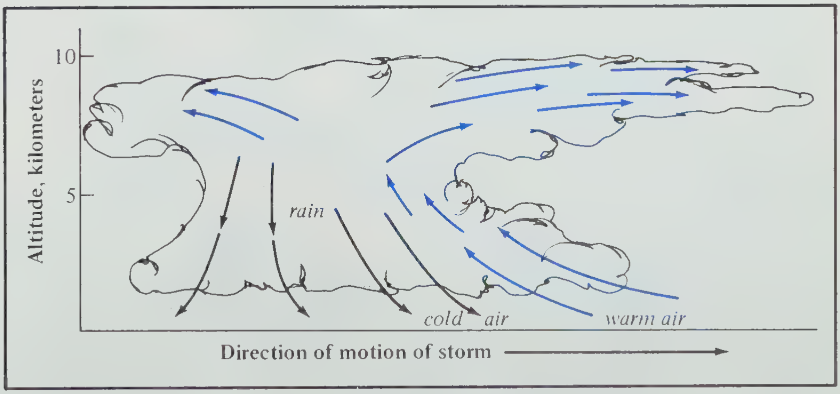


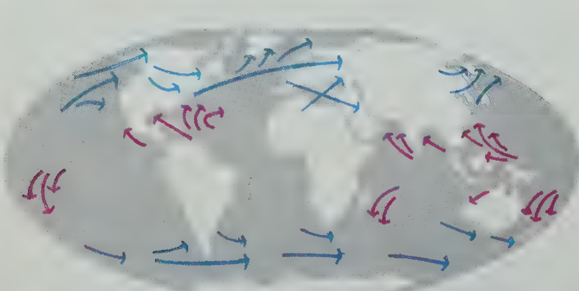
Figure 7–9
A tornado usually develops from a large cumulonimbus cloud.

to a kilometer in diameter. (See Figure 7–9.) The pressure is low within the funnel cloud of a tornado. The sudden drop in pressure as a tornado passes can cause the walls of houses to blow outward explosively.

Tornadoes seem to be caused by intense convection. Some scientists suggest that continuous lightning within a cloud may release intense heat that starts the convection or increases it. Recent pictures of tornado damage show that convective cells stronger than the main tornado may rotate around the center of the larger "twisters." About one-tenth as large as the main storm, these cells have been called "suction spots" because they act like a powerful vacuum cleaner.

The tornado's winds can reach speeds of 250 miles per hour or greater. The tornado develops from a large cumulonimbus cloud that is rotating slowly, perhaps because the air moving into it already has a spinning motion. When intense convection starts at some point in the cloud, air rushes in to replace the rising mass. Since the inflowing air is already spinning, it spins faster and faster as it converges toward a center. If you twirl a weight tied to a string around your finger, the weight moves faster as the string winding around your finger becomes shorter.

Figure 7–10
The typical paths of polar front cyclones (blue) and tropical cyclones (red).



Action *Create a vortex or whirlpool in your wash basin or bathtub by partly filling it with water. First, direct the water toward one side as you let it pour in. Then release the drain. As the water flows out, note the direction in which the vortex rotates. The next time, direct the*

water toward the other side. The water has a spinning motion to begin with. It spins more rapidly in the same direction as it converges toward the drain, because it makes smaller and smaller circles. Can you explain why tornadoes rotate in the same direction as cyclones?

Polar front cyclones occur in middle latitudes. In the tropics another kind of cyclone develops. These tropical cyclones of low latitudes are called **hurricanes** in the Western Hemisphere. In the Pacific, they are called **typhoons.** They are less frequent than polar front cyclones. Hurricanes always develop over the warm waters of the tropical ocean. Compare the typical paths of tropical and polar-front cyclones in Figure 7–10.

Figure 7–11 is a spectacular view of a hurricane taken from space. The bands of cumuliform clouds spiral inward toward the eye of the hurricane. Around the center of the storm, the clouds develop into huge cumulonimbus cells that ring the eye of the storm. The energy that drives a hurricane comes from the release of latent heat supplied to the clouds by the warm ocean waters.

Although the formation of tropical cyclones is not well understood, they often develop when the Intertropical Convergence Zone is several degrees away from the equator. The hurricane's rotating winds, which may exceed 150 miles per hour, result when air flowing inward toward a low pressure center is deflected by the earth's rotation. The strong winds and low pressure of the storm cause mountainous waves and tides.

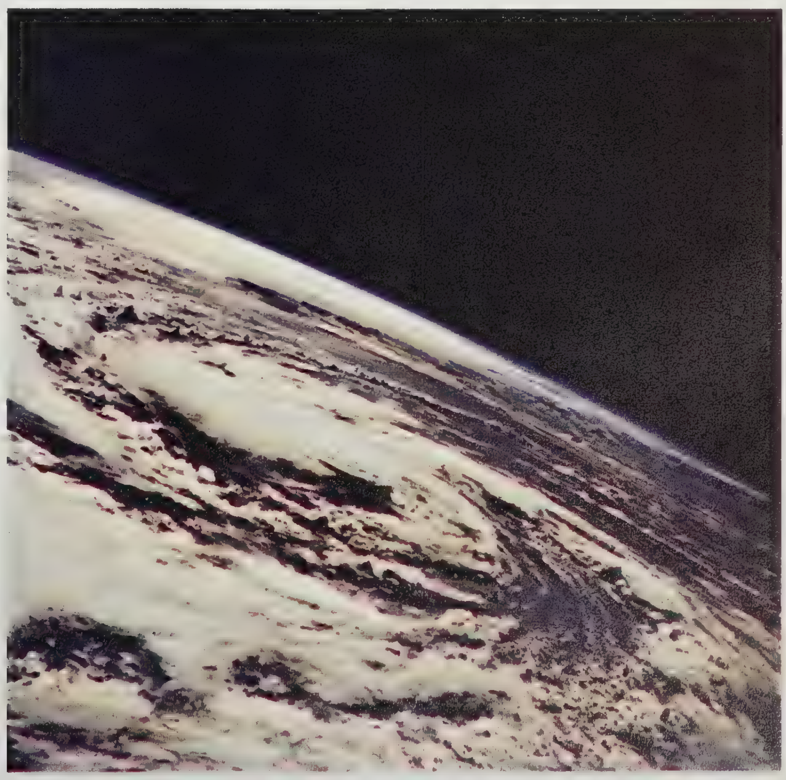


FIGURE 7–11
An Apollo 7 photo of a hurricane off the Florida coast. The eye of the storm is hidden by a pancake of cirrostratus clouds. Why don't we have a picture of an anticyclone?

Although the hurricane winds are very destructive, the greatest damage and loss of life are caused by the waves and exaggerated tides that accompany the storm. Figure 7–12 shows the life history of hurricane "Camille."

Thought and Discussion

1. How does a cyclone transfer heat: upward or downward? Toward the pole or equator?
2. When air converges, it develops cyclonic rotation. When it diverges, it develops anticyclonic rotation. Would this happen if the earth were not rotating?
3. In Chapter 1 you learned that the earth rotates in space around every point on its surface except at the equator. Tropical cyclones do not develop right at the equator. Are these facts related?

Climate and the Water Cycle

7–7 The general circulation and patterns of climate

Climate may be considered the history of weather over a period of time. The word "climate" comes from the Greek *klima,* meaning "sloping surface of the earth." The Greeks knew that the climatic zones of the earth were related to the inclination of the sun's rays.

Remember that the atmosphere's capacity to hold water vapor depends on the temperature of the air. Look at the evaporation bars in Figure 7–13. You can see that insolation must be the principal factor affecting evaporation at

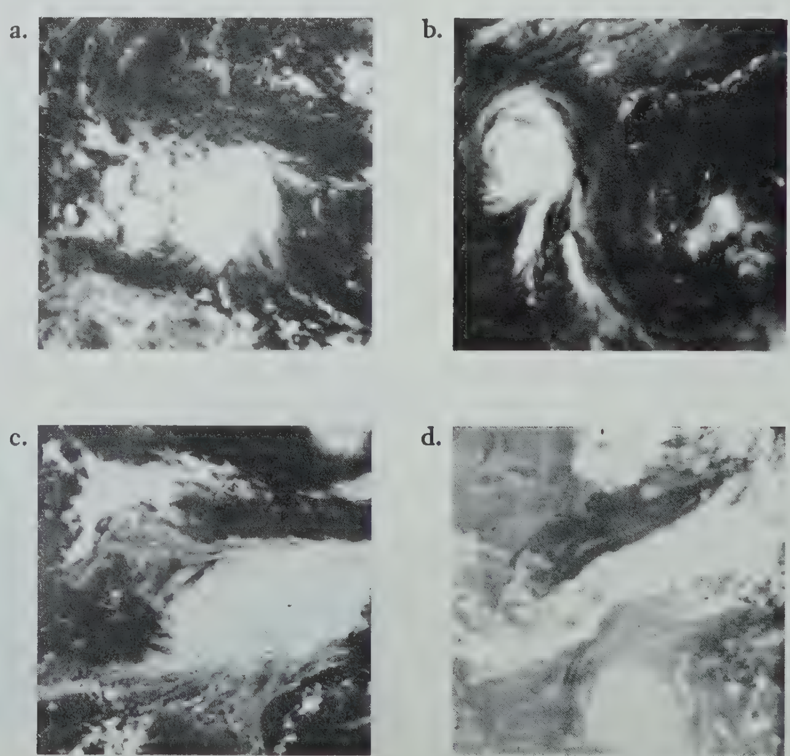


FIGURE 7–12
Development of hurricane Camille.
a. *August 11, 1969. Camille begins to take shape in the Caribbean.*
b. *August 17. The winds reach 190 to 200 miles per hour. The storm causes a 25-foot tidal wave.*
c. *August 19. The lessening storm brings torrential rain to the land as it moves north.*
d. *August 21. While Camille fades, hurricane Debbie develops behind it.*

the earth's surface. The curve sinks almost to zero at the North and South poles where the insolation is lowest.

Figure 7–14 is a world map of precipitation. Notice the low rainfall zones between latitudes 25 and 30 degrees north and south. There is more evaporation than precipitation in these regions of the trade winds. The trades come from the sinking air of the subtropical highs. They are therefore very dry and can absorb

FIGURE 7–13
Annual precipitation and evaporation vary with latitude.

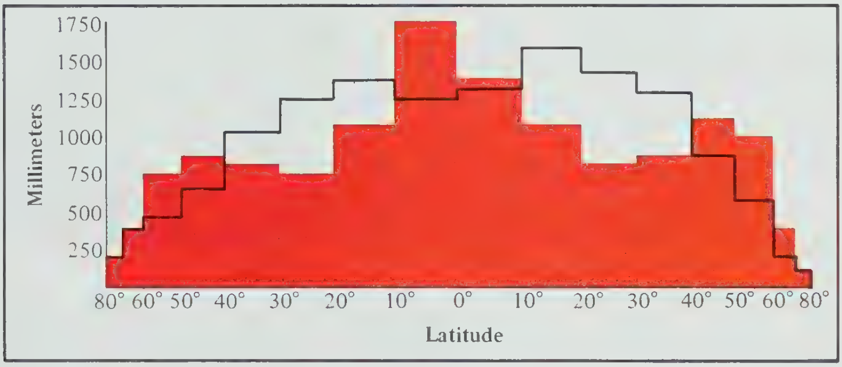
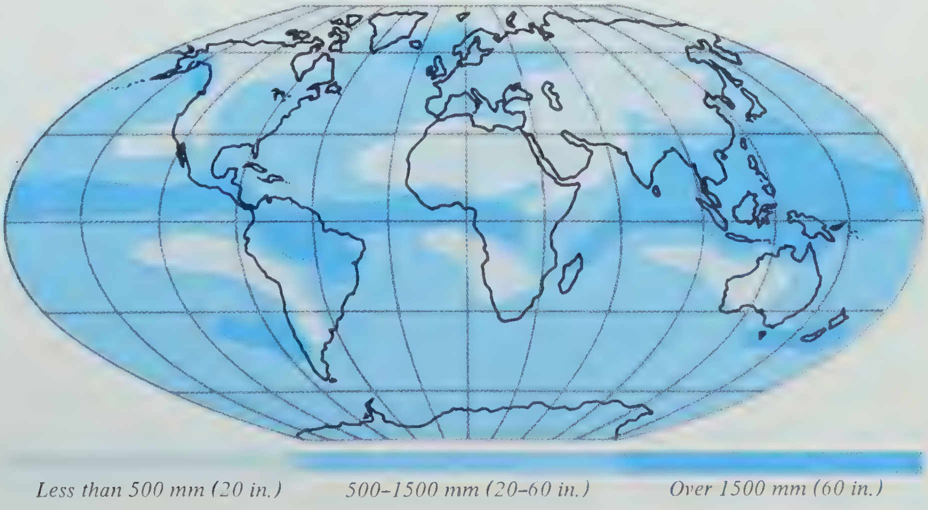


FIGURE 7–14
Total annual precipitation of the world.



vast amounts of moisture. As you might expect, the earth's dry climates occur in these regions.

Notice the belt of heavy precipitation near the equator. Here precipitation is greater than evaporation. The trades carry moisture into the Intertropical Convergence Zone where the air rises and the moisture condenses. On the average, the convergence zone between the trades is located north of the equator. What kind of climate would you expect in this region?

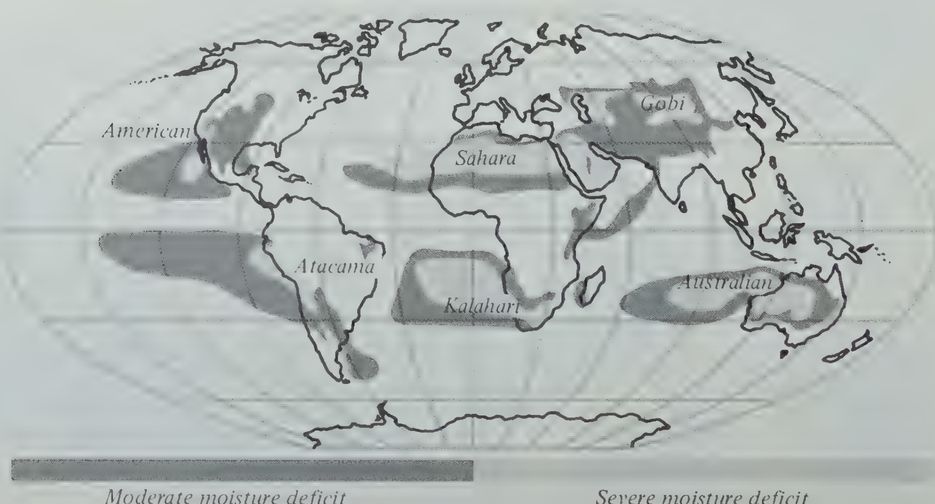
There is also a zone of heavy precipitation at 40 to 50 degrees north latitude. This is the region of the westerlies and the polar front, where cyclones and anticyclones occur. The moist tropical and subtropical air masses in the cyclones produce regions of ample rainfall in each hemisphere. This zone is not continuous around the earth. Land, oceans, and mountains influence the paths of cyclones and the amount of rain they bring.

Deserts are generally found in the core of dry regions. If you compare Figures 7–14 and 7–15, you will notice that areas of light precipitation extend from the deserts of North America and Asia into the polar region. The northern parts of these continents receive the same amounts of rainfall as the desert regions, but they are not deserts. The temperature, and therefore evaporation, is so low that even the small amount of precipitation that does occur is greater than the evaporation.

7–8
Geography influences climate.

Oceans and continents interrupt the basic latitudinal pattern of climate. Both temperature and moisture patterns are affected. The map in Figure 7–16 shows the average temperature changes between winter and summer. The in-

FIGURE 7–15
Areas of the world with a moisture deficit or a dry climate. The name of the major desert in each region is given.



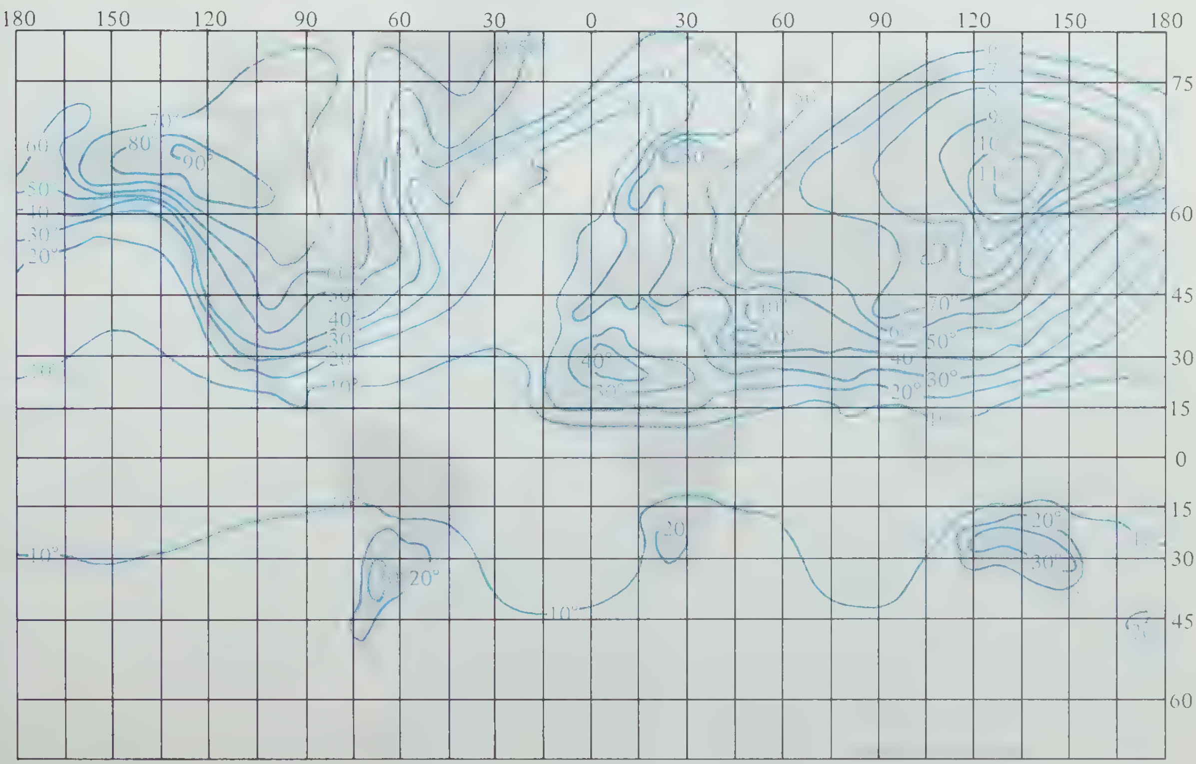
teriors of continents are generally hot in summer and cold in winter. They are said to have **continental** climates. **Marine** climates have smaller temperature changes from winter to summer.

Action *Turn back to Figure 6–8 and follow the 60 degrees north latitude circle. Write down the July temperatures over the Gulf of Alaska, Central Canada, the Atlantic Ocean north of Great Britain, and eastern Asia. Write down the values for the same points in January. (See Figure 6–9.) Now compute the difference in temperature from July to January for each of the four points. Which location has the greatest annual range of temperature? Which has the least? Compare the seasonal temperature changes along 60 degrees south latitude. Compare the temperature range at 60 degrees south latitude and 60 degrees north latitude.*

The size of a continent affects both the temperature range and the amount of moisture in the interior. The larger the continent, especially

Figure 7–16

Map of annual temperature ranges. The numbers show the difference in average temperature in °F between the warmest and coldest months. How do land masses affect the annual temperature range?



WLADIMIR KÖPPEN

Köppen (1846–1940) grew up on the coast of the Black Sea in Russia where the climate is mild and the vegetation rich and subtropical. Köppen loved the landscape and was impressed by the close relationship of the climate to vegetation. When he was 21, he started to work on a system of classifying climates by plant distribution.

Later, he revised his classification of world climates, basing it on annual and monthly records of temperature and precipitation. Köppen's five major climatic groups are: 1) tropical, rainy climates, 2) dry climates, 3) rainy climates with mild winters, 4) rainy climates with severe winters, and 5) polar climates. The system he devised is used throughout the world, and many new classifications follow the basic ideas of his system.

As a chief meteorologist at the German Naval Observatory, Köppen investigated the upper air by kites and sounding balloons. He produced a series of maps showing the average velocity and direction of winds on the oceans.

About 1918 Köppen became interested in the idea of continental drift. His son-in-law Alfred Wegener, a geologist, had presented this idea. They moved to Austria and made excursions into the Alps, even though Köppen was now in his 70's. Together they published a book on the climates of past geologic ages. They based their conclusions on the shifting of the earth's poles.

in middle latitudes, the greater the temperature range and the greater the tendency for strong monsoons to develop.

At latitude 40 and 50 degrees, cyclones usually are carried from west to east by the strong westerly winds that sweep around each hemisphere. Therefore, polar-front rainfall is heaviest on the western sides of the continents. Air masses from the Gulf of Alaska carry moisture to western Canada and the United States. In summer these air masses are relatively cool, and in winter relatively warm, but they are always moist. Therefore, coastal areas of the northwestern United States have high humidity and abundant rainfall. Conditions are similar in northwestern Europe.

Cyclones moving eastward across a continent lose most of their moisture before reaching the interior. The climate becomes progressively drier farther inland along the same latitude. In the deep interior of the continent, far from ocean sources of moisture, there is little precipitation and therefore little evaporation. The air remains dry and the skies clear. One example of a dry continental climate is the Gobi Desert in Central Asia. (See Figure 7–17.)

Ocean currents also have an important influence on the temperature and moisture of neighboring land areas. Oceans store heat during the summer and release it slowly in the winter. Warm currents flow poleward along the eastern sides of continents. A cold air mass

moving over the warm Gulf Stream, for example, will be warmed at the base. Because the air remains cold in the upper levels, the air mass becomes unstable as it is warmed from below. Cloudiness and rainfall develop in the moist, unstable air.

Air moving around the subtropical high pressure areas (Figures 6–12 and 6–13) blows along the western shores of the continents toward the equator. This flow produces cold surface currents along the shore. An air mass moving toward the coast of southern California is cooled

Figure 7–17
a. *Polar front cyclones bring almost 80 centimeters of moisture a year to the coast of France.*
b. *The Gobi Desert at the same latitude receives less than 10 centimeters.*

a.

b.

at its base by the cold water offshore. This type of air mass is stable and tends to resist vertical motions. Fog may result from condensation in the lower part of the air mass, but rain is unlikely. Notice in Figure 7–15 that the great deserts of the world tend to be located on the eastern sides of the oceans in the subtropics.

We can now summarize the causes of dry climates. The pattern repeats from continent to continent. Look at the Northern Hemisphere in Figure 7–15. The desert regions on the western sides of the continents at 25 to 30 degrees north and south latitude are caused by sinking, dry air from subtropical high pressure areas. The dry air is cooled and stabilized by cold ocean currents. The coastal deserts extend into the continental interiors. These interior deserts are too far from ocean sources of moisture to receive much precipitation. The warm ocean currents and the onshore flow of unstable air keep the eastern sides of North America and Asia moist.

7–9
Mountains further modify the pattern.

The shift from a dry region to a wet one is generally gradual. However, mountains can cause sharp boundaries between different climatic zones. Mountains channel air movements and affect fronts and cyclones. For example, during most of the winter, cold air moving down from Canada is held east of the Rocky Mountains as it flows southward. But polar air can sweep across the central plains of North America into and beyond the Gulf States, sometimes freezing the citrus crops of Florida. The Rockies usually prevent such polar air masses from damaging citrus crops in California.

Mountains lying near the shores of oceans prevent marine air at the earth's surface from penetrating far inland. Such a barrier exists along the Pacific coast of North and South America. In Asia the Himalayas help keep the Indian winters mild, while northern China and Korea are not protected from cold winds blowing out of the continental interior.

Highlands also have a marked influence on the amount and distribution of precipitation. In mountains most precipitation falls on the slope the wind is blowing against when the air rises to flow over a mountain range. Little rain falls on the other side of the range where the air descends and dries out. A dry area on the downwind side of a mountain barrier is said to lie in the rain shadow of the mountain.

Mountains also differ in climate from lowlands. Since air temperature decreases with altitude, it is possible for snow to last through the summer and glaciers to form.

7–10
Investigating the climates of an imaginary continent

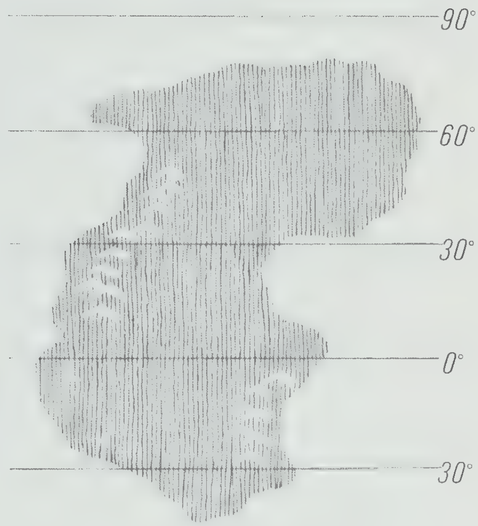
You have studied some of the factors that control the world's climates, such as insolation, the atmosphere's circulation, and the location of oceans, continents, and mountains. Now use this knowledge to outline the climates of an imaginary continent on the earth.

PROCEDURE

On the outline map (Figure 7–18) that will be supplied by your teacher, try to identify the climatic regions of the imaginary continent.

1. *Locate the major latitudinal zones of converging and diverging air masses. In each case, indicate which are the wet zones and which are the dry zones.*
2. *Sketch in the boundaries between climatic regions on the imaginary continent. Start by outlining the dry regions. Label all regions by their temperature and moisture conditions, such as hot, warm, or cold and humid or dry.*
3. *Explain the temperature and moisture conditions in terms of latitude, land-water differences, mountain ranges, air motions, and the differences between evaporation and precipitation.*

FIGURE 7–18

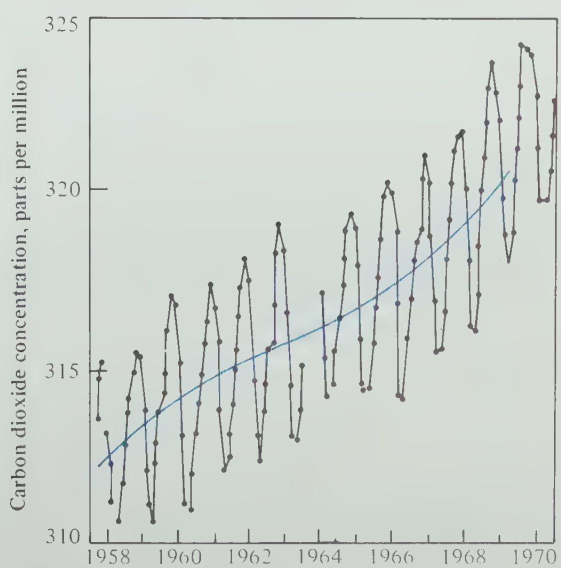


7–11 The changing atmosphere and climates

Natural processes combine to keep the amount of gases in the atmosphere fairly constant. For example, lightning removes nitrogen from the atmosphere, while the decomposition of organic matter restores it. Volcanic eruptions add nitrogen, carbon dioxide, and water vapor. During photosynthesis, plants convert carbon dioxide and water into plant tissue and release oxygen into the atmosphere. But animals take in oxygen and exhale carbon dioxide. The seasonal changes in vegetation cause a slight change in the carbon dioxide concentration in the atmosphere. (See Figure 7–19.)

Before life appeared on the earth, the atmosphere probably consisted of a thin layer of

FIGURE 7–19
Changes in the amount of carbon dioxide in the atmosphere at Mauna Loa, Hawaii.



methane (CH_4), ammonia (NH_3), water, and small amounts of hydrogen, oxygen, nitrogen, and carbon dioxide. The first living organisms were formed in this mixture.

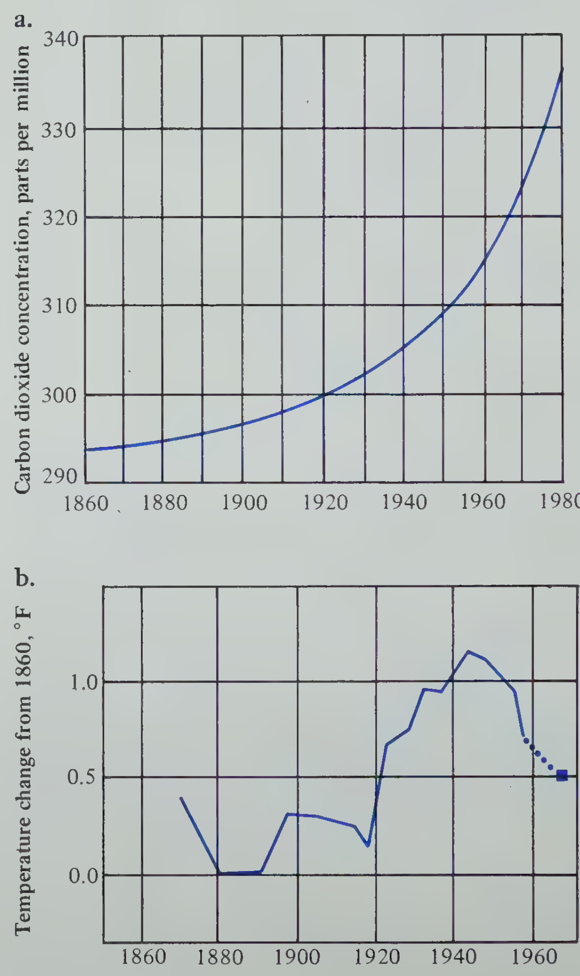
Life probably originated in the sea, perhaps under rocky ledges where it would not be destroyed by the sun's ultraviolet radiation. As plants contributed oxygen to the atmosphere, the sun's ultraviolet rays broke up some of the oxygen molecules and ozone (O_3) appeared. A protective layer of ozone accumulated high in the atmosphere, shielding the earth's surface from too much ultraviolet. Life could then spread. Some oxygen was present in the original atmosphere, for water vapor was also broken up by ultraviolet radiation. The lighter hydrogen molecules escaped from the earth's gravitational field, and oxygen atoms remained.

Photosynthesis brought the oxygen to its present level (21 per cent) and maintains it there. Many processes keep the atmosphere's nitrogen at its current value (78 per cent).

Carbon dioxide is one of the gases that keep the earth's surface warm. As organic materials decay, carbon dioxide is released into the atmosphere. There is a continuous exchange of carbon dioxide between the oceans and the atmosphere. There is good evidence that burning of coal and oil has caused an increase in carbon dioxide in the earth's atmosphere from the 1880's to the present. (See Figure 7–20.) Because of the greenhouse effect, an increase in carbon dioxide should cause the earth's surface temperature to rise.

Attempts have been made to predict the effect of greater energy consumption on the future amount of carbon dioxide in the atmosphere and its effect on the earth's climate. Such predictions are uncertain, however, because warming might cause more evaporation, more cloudiness, and cooling. But warming the oceans might also cause the release of even more carbon dioxide into the atmosphere, resulting in even more warming.

Figure 7–20
a. *The amount of carbon dioxide in the atmosphere has increased since 1880.*
b. *Until recently, the temperature of the earth was also rising.*



Notice in Figure 7–20 that the increase in carbon dioxide in the 1880's was paralleled by an increase in temperature until the early 1940's. The temperature then began to fall, even though the amount of carbon dioxide continued to increase. Some scientists suggested that an increase in atmospheric dusts caused by pollution could have offset the expected warming from the increased carbon dioxide. But other scientists have used the evidence to show just the opposite.

Dust is present naturally in the atmosphere. Following the eruption of Krakatoa in 1883, volcanic dust remained in the atmosphere for about five years. Fine dust particles in the stratosphere probably reflect the sun's radiation and result in cooling. The Northern Hemisphere summers were cooler after the eruption of Krakatoa.

In the 1960's, the earth's average surface temperature was falling at a rate of about 2.2°F per century, but the causes of the cooling were uncertain. Dusts produced by man's activities do not normally penetrate the stratosphere. It is not yet known whether they produce a net cooling or warming effect on the surface temperature.

7–12
Causes of ice ages

More than 60 hypotheses have been proposed to explain the ice ages. Some earth scientists believe that changes in the land and water masses close to the poles set the stage for the ice ages. Mountains and land-locked seas close to the earth's poles would favor snow and ice. In mountains and highlands, the snows of winter tend to stay through the summers. If polar seas are landlocked, or nearly so, ocean currents cannot transfer heat into the polar regions.

When ice sheets are formed, they tend to persist and grow. On the average, the earth and its atmosphere reflect about 30 per cent of the solar radiation. However, ice reflects about 70 per cent of the insolation reaching it. When large areas of snow and ice last through the summers, much more solar energy is lost to space. The summer circulation pattern becomes more like that of winter, and more snow falls to feed the glaciers.

The cold glacial periods may have appeared after a series of mild winters and cool summers. In mild winters, the polar front is located far to the north of its average position in the Northern Hemisphere. Then more snow falls in winter at these latitudes, instead of farther south. In cool summers, there is less melting of the winter snowfall. Thus, after many mild winters and cool summers, the polar ice sheets could spread toward the equator. To explain the reversal of an ice age, scientists usually assume a reversal of the conditions that produced it. When warmer summers returned, the ice would melt.

Astronomers have pointed out that relatively mild winters and cool summers at high latitudes can result from slow changes in the earth's motions around the sun. These changes, every 360,000 years, provide more radiation at high latitudes during winter, and less in summer. Attempts have been made to relate this cycle of changes in insolation to known glacial and interglacial periods. The onset of a glacial

period is gradual (about 90,000 years), but the warming is sudden (about 10,000 years). (See Figure 7–21.)

7–13
Urban influences on climate

The climates of densely populated, industrialized areas are different from those of rural areas. The cities studied have less sunshine and, usually, lower wind speeds than the surrounding country. These cities are cloudier, foggier, and warmer than the country. They have lower relative humidity but more precipitation.

The added heat from homes and industries is believed to cause rising air currents over cities and therefore more clouds. The increased amount of dust affects solar radiation and acts as condensation nuclei for clouds, fog, and haze. It is not known whether dust contributes to the warming of cities, or whether it has a cooling effect.

Meteorologists can point to the records of city climates, compared with those of rural areas, to show that people are changing their local weather and climate. There is evidence of an increase in the world's carbon dioxide content and of dust particles in the atmosphere north of latitude 30 degrees. But whether these changes affect the global climate is unclear.

Thought and Discussion

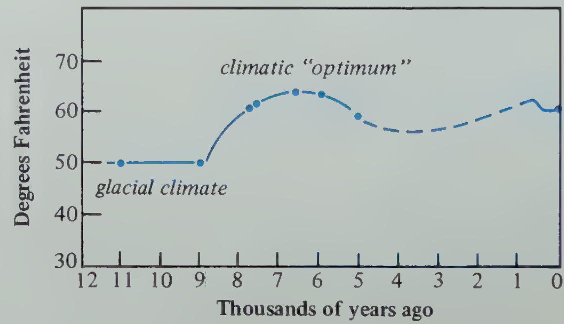
1. There is very little water vapor in the stratosphere. If water vapor were put there by some means, would it tend to remain for a long time?
2. Dust in the stratosphere helps cool the earth's surface, while dust near the earth's surface may have an opposite effect. Can you suggest why the effects might be different?

Unsolved Problems

Fluctuations in the earth's climate over tens, hundreds, and thousands of years are still one of the unsolved problems of earth science. We know that periods much colder and much warmer than the present have occurred in the past, long before man built fires—indeed, long before *Homo sapiens* appeared on earth. On the scale of decades, the temperature trend is downward. On the scale of thousands of years, the trend is upward.

The most probable causes of climatic changes are the following:

Figure 7–21
The changing climate of the Mediterranean region.



- Changes in the atmospheric circulation
- Changes in the ocean-atmosphere system
- Volcanic dust in the stratosphere
- Carbon dioxide from fossil fuels
- Solar variations
- Changes in the deep ocean circulation
- Changes in the polar ice caps
- Changes in the earth's axial and orbital positions
- Natural variations in the carbon dioxide in the atmosphere
- Mountain building and continental uplift
- Continental drift
- Polar wandering
- Changes in the mass and composition of the atmosphere
- Galactic dust
- Gravitational waves in the universe
- Evolution of the sun

You are already familiar with some of these causes of climatic change, and you will learn about others later in this book. To understand climatic changes, the more important factors have to be studied simultaneously and quantitatively. Our understanding of climatic changes is still piecemeal and qualitative. Therefore we cannot yet predict future changes in the earth's climate with any accuracy.

Scientists use computers to study the causes of the earth's climate. They trace the flow of solar energy and of air and water in the earth's atmosphere and ocean to make climatic models. Using such models, they should eventually be able to estimate the importance of each possible cause of climatic changes, including man-made changes in the environment.

Chapter Review

Summary

The vertical air motions that cause precipitation occur mainly at the polar front and in the equatorial zone. The potential energy of air masses on either side of the polar front is released when cyclones and anticyclones form in the westerlies. The cyclones go through a life cycle, beginning with a disturbance on the polar front and often ending with the occluded cyclone that dies away because its energy source is gone.

The general circulation also includes smaller motion systems. Most of these systems are visible features of the water cycle because they involve condensation and cloud formation. Thunderstorms, tornadoes, and hurricanes depend on the release of latent heat for their development and maintenance.

Climate can be thought of as the summary of weather history. Weather is an actual occurrence. Climate is a generalization from weather records. It is the average weather for a given region over a long period of time.

The global climate varies with latitude because solar energy is distributed unevenly. A belt of heavy precipitation marks the zone where the trade winds converge. Other zones of ample precipitation occur at 40 to 50 degrees latitude in the region of the polar front. Deserts are located in the zones of the subtropical highs. The cooling, sinking air of the polar zones is very dry and yields little precipitation.

The latitudinal pattern of climate is modified mainly by continents and oceans. Continental climates have a wider range of temperatures than marine climates. The low rainfall zones at 25 to 30 degrees and the high rainfall zones at 40 to 50 degrees are restricted to the western sides of continents.

The causes of large climatic changes over long periods of time are still uncertain. However, studies show that urban areas produce local and possibly regional climatic effects by introducing wastes into the atmosphere. These wastes include heat, water vapor, and particles that act as condensation nuclei.

Although man-made environments can change local climates to some extent, man exercises little actual control over the water cycle in the atmosphere. When water reaches the land, he has a greater opportunity for control.

Questions and Problems

A

1. Describe the stages in the development of a polar front cyclone. Why is a cyclone usually accompanied by an anticyclone?
2. Tropical cyclones usually lose force when they move over a large land area. Why?
3. Small whirlwinds called "dust devils" rotate either clockwise or counterclockwise, although tornadoes rotate cyclonically. Can you suggest why?
4. Where are the wet and dry belts in the basic climatic pattern of the earth and how are they produced?

B

1. The polar front has been far north of its usual position for the past month. Was the rainfall during this period along the usual position of the polar front greater or less than normal?
2. A rapidly occluding cyclone has just passed over your area. Would you expect the forward movement of the storm to speed up or slow down during the next 24 hours?
3. At the advanced stage of a glacial period, the average temperature of the earth may be lowered by about 9°F and the ocean temperatures would also be colder. How would this affect the amount of evaporation?

C

1. Explain how periodic changes in the earth's position in its orbit *could* cause the polar ice caps to spread toward the equator.
2. Why do cyclones rotate in opposite directions in the Northern and Southern Hemispheres?
3. How do mountain ranges affect the climate where the wind blows moist air against them?
4. Why are the interiors of continents likely to be dry?
5. Very little precipitation occurs in the polar regions, yet these regions are not deserts in the true sense of the word. Why?

Suggested Readings

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Thompson, Philip D., O'Brien, Robert, and the editors of *Life*, *Weather*. Time, Inc. (Life Science Library), New York, 1965.

8. Waters of the Land

The earth has been recycling its water for three billion years. The distribution changes, but the total supply remains constant.

When the atmosphere releases fresh water upon the land, people get involved in the water cycle. Rivers and lakes are our main source of fresh water for drinking, cleaning, and irrigation. Before the invention of the steam engine, waterways were the major route for the exchange of people, goods, and also ideas. For many of us, fresh water also provides recreation and natural beauty. However, rivers and lakes are also used to get rid of municipal wastes.

In some river valleys, like the Nile, people have depended on flooding to enrich the soil each year. But in many regions floods are natural disasters. Spring floods are caused by melting snow and seasonal rains over great river basins.

Throughout much of history, man's dependence on water has led him into great enterprises to control the waters of the land. Some of these attempts have not turned out well because all of the consequences could not be foreseen. The water cycle is far from being completely described in quantitative terms.

When rain falls upon the earth, some of it flows over the surface of the earth into streams, some evaporates, and some seeps into the ground. The picture on the opposite page shows a visible part of the land-based water cycle. You do not see, of course, the flow of invisible water vapor from the land back into the atmosphere. And ordinarily we are unaware of the reservoir of water beneath the earth's surface. But the storage and flow of water beneath the surface is one of the primary concerns of earth scientists.

Moisture Income and Storage

8–1 Where does fresh water come from?

During the time of the Roman Empire, some people in North Africa and the Middle East drank dew. They used large piles of rocks located over catch basins to collect their drinking water. Dew condensed on the rocks and dripped into the basin below. In the ancient city of Theodosia on the shores of the Black Sea, these basins, also called "surface wells," collected about 15,000 gallons of water a day.

Fog is another source of moisture. In some places, dense fogs form as warm, moist air masses are cooled by cold ocean currents. The fogs blow into the coastal hills and mountains. Moisture is caught by trees and shrubs and drips to the ground below. This moisture keeps plants growing in areas where rain seldom falls, as in the coastal desert of Peru. Along the coast of California, fogs supply additional moisture to the dense redwood forests. (See Figure 8–1.)

Rain and snow are by far the major sources of fresh water for living things. Precipitation varies from place to place, from one season to another, and from year to year. The amount that falls in a given time also varies. Figure 8–2 shows the world's record amounts of rainfall observed for different time periods. Some occurred with thunderstorms, others with tropical cyclones, and others were produced by monsoon rains.

In some deserts, rain is so uncommon that the natives do not have a word for it. Yet in

FIGURE 8–1
Fog rolling into a forest along the coast of California. Trees and shrubs benefit from this moisture.

tropical areas such as the Amazon basin it rains nearly every day. Do you know how often it rains where you live? What are some of the ways you could find out?

Figure 8–3 shows what happens after precipitation reaches the earth. Consider a single raindrop. It might soak into the ground, run off, or evaporate. You might think that rivers and streams are the main carriers of water from the land. However, only about one-third of the precipitation falling on the continents runs off in streams and rivers to the ocean. About two-thirds returns to the atmosphere by evaporation from soil and plants.

FIGURE 8–2
Extreme rainfalls of the world. Record rainfalls in a short period of time generally occur with thunderstorms. The Cherrapunji extremes were produced by monsoon rains.

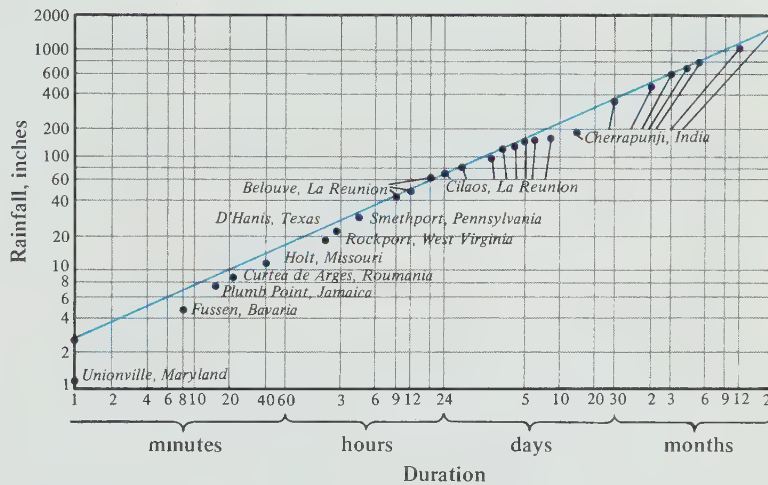
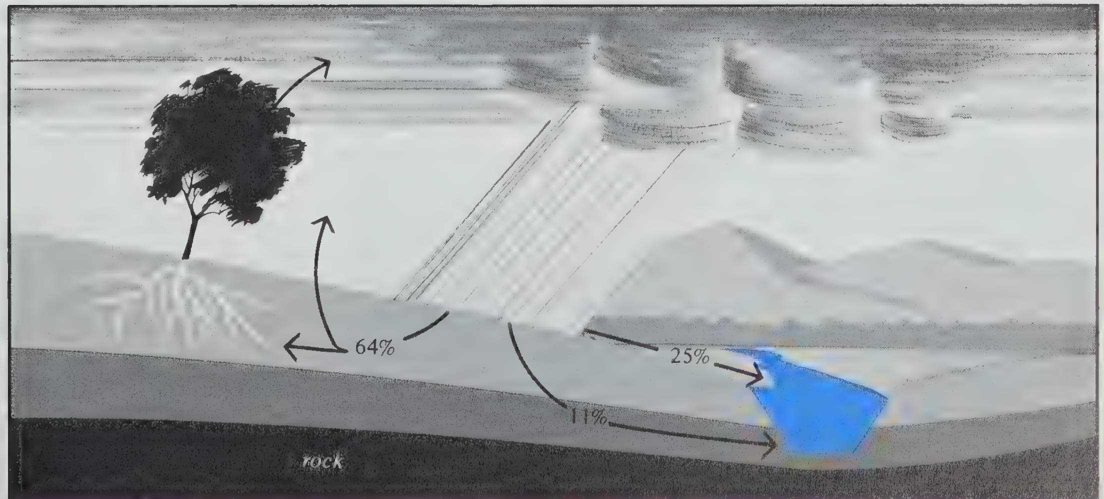


FIGURE 8–3
Of the total precipitation that falls on the continents, sixty-four per cent returns to the atmosphere through soil and plants. Eleven per cent reaches streams by moving below the surface. Twenty-five per cent runs off directly.



8–2
How fresh water is stored

Most of the fresh water stored on the earth is frozen in glaciers. There are about 30,000,000 cubic kilometers of ice now on the earth's surface. If all the ice and snow on the earth were melted, the level of the ocean would rise an estimated 30 to 60 meters.

Glaciers are huge, slowly flowing masses of snow and ice. (See Figure 8–4.) They form where the winter snowfall is greater than summer melting. Snow then accumulates from year to year. As the snowfields become thicker, the lower layers are compacted and finally turn into ice. Glaciers located on slopes flow downhill, and those located on level ground flow outward from the middle. A glacier that has stopped flowing is said to be "stagnant" or "dead."

Some glaciers form in mountain valleys or bowl-shaped areas on mountain slopes where snow has accumulated. Others build on the lee side of ridges, where drifting snow is left by the wind. Much larger glaciers, usually called **ice sheets** or **ice caps**, occur in Greenland and Antarctica. These are survivors of the last ice age that once covered a much larger part of the continents.

The balance between snowfall and melting determines whether a glacier grows or shrinks. Glaciers on the west coast of Greenland increased in size from 1850, when they were first surveyed, until the 1860's. Since that time they have been retreating. Although the average temperature of the earth has fallen since the late 1940's, not all glaciers have been altered by this change. In some regions of the earth they have advanced, but in other places they continue to shrink.

The rate at which glaciers melt depends partly on the reflectivity of the snow surface. The heat that isn't reflected is absorbed. Fresh snow may reflect more than 80 per cent of the sun's radiation. In time, however, the form of the crystals changes, and old snow may reflect less than 50 per cent of the sun's energy. If the winter snowfall is *greater* than normal, melting during the following summer can be *less* than normal. The fresh snow reflects more energy, and less is available for melting. (How might the melting of glaciers be artificially controlled?)

In addition to glaciers, the snowfields of the world store a considerable amount of water. Every 10 to 15 millimeters of snow yields one millimeter of water, depending on the density of the snow. Snow accumulates during the cold season in each hemisphere. The greatest amounts of snow fall at high elevations and on the margins of the cold polar regions. Most of this snow melts in the spring. Only small amounts fall in the coldest areas of the earth, because the cold air contains little water vapor. However, most of this water within the polar regions is held in storage because evaporation and melting are slow.

Much of the water melted from snow runs off the land into streams and lakes. Almost all of it does when the water in the soil under the snow is frozen. If the soil beneath the snow is not frozen, melted water soaks into the soil and adds to the water supply in the ground. Of

course, rainfall also soaks into the ground. If the rainfall is light, most of it may evaporate from the soil surface. If the rainfall is heavy and continuous, a considerable amount may filter down into the soil.

Rain water moves downward into pores or holes in the loose soil until it reaches rock. The "solid" rock below the soil is called **bedrock.** Bedrock can have fractures, cracks, and other openings that store additional water. Some regions, such as New England, have only a thin layer of soil. There, most of the subsurface water is found in the pore spaces or fractures in bedrock.

Sandstone and other porous sedimentary rocks can also store great quantities of water. The lake behind the Aswan Dam in Egypt has not filled up as quickly as planners hoped it would. One reason is that the 300-mile-long western bank is largely sandstone and absorbs seemingly endless amounts of water.

Finally, lakes are an important form of water storage in many parts of the world. If soil becomes saturated and the rain comes down faster than it can soak into the soil, water begins to run over the land. Some of this runoff may flow into low areas and form lakes. They regulate streamflow and provide water for cities and farms. Many natural lakes have been modified for greater storage capacity by controlling the amount of water that flows out of them. New lakes are also created by damming rivers.

FIGURE 8–4
Great amounts of fresh water are temporarily stored in glaciers like this one in Alaska.

Action Find out where your drinking water comes from. What steps are taken to treat the water before you use it?

8–3
Investigating the movement of water in earth

You have probably noticed water seeping or flowing from a hillside. Do you have any idea how fast ground water moves through pore spaces in earth materials? Can water move upward through soil? What affects the flow of water underground? In this investigation you will find evidence to answer some of these questions.

Procedure

Set up the column as shown in Figure 8–6. Your teacher will provide you with some different-sized particles. Place 100 milliliters (ml) of uniform-sized particles in the column. Make sure the wire screen is in position to prevent the particles from running out.

1. *Find the volume of water necessary to **just** cover the upper surface of the particles. What per cent is it of the total volume (100 ml) occupied by the particles? This is the percentage of space between the particles and is called the **porosity**.*

*Open the clamp and allow the water to run out. Record the amount of water retained by the particles. Add 300 milliliters of water to the cylinder holding the grains. Record the time required for the water to drain through the particles. This is a measure of **permeability**, the rate at which water can pass through a porous material. Repeat the procedure using the other sizes of particles.*

2. *Make a graph to see if the diameter of the particles seems to affect porosity. Explain your results.*
3. *Make a graph to see if the grain size seems to affect the amount of water retained in the column after draining.*
4. *Make a graph to see if the size of the particles affects the rate water flowed through them (300 ml ÷ time).*

*To see if water can rise through the soil, set up the apparatus as shown in Figure 8–7. Use 200 milliliters of fine dry sand in the tube. When your partner is ready to time, lower the tube into the water so that the base is **just** beneath the water surface. Time and record any change in water level in the tube at 30-second intervals.*

5. *What do you think accounts for movement of water upward in the tube?*

8–4
Water moves into the ground.

Water moves downward rapidly in sand because both the sand grains and the pore spaces between the grains are large. Clay, however, has very small pore spaces. Most soils contain both clay and sand. Many of these clay and

FIGURE 8–5
Water pouring from a road cut. Are there places like this is your neighborhood? Have you ever stopped to inspect them?

FIGURE 8–6

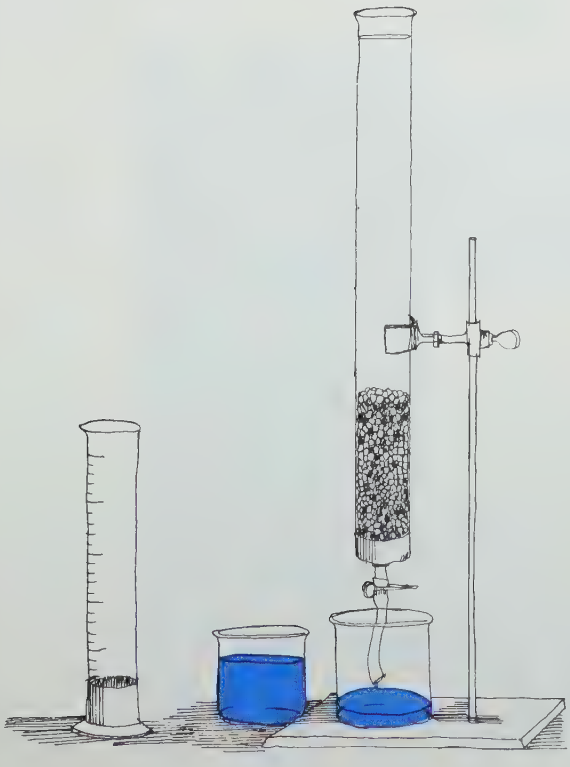
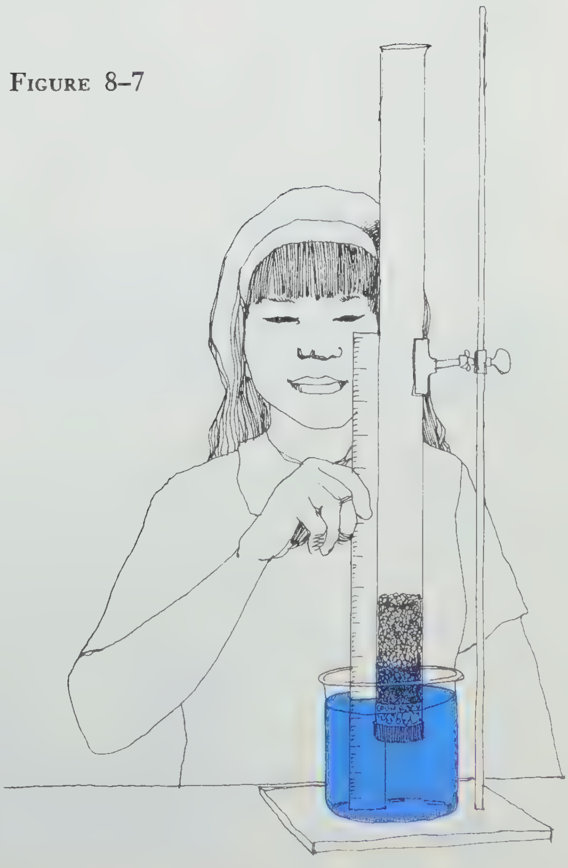


FIGURE 8–7



sand particles are held together in clusters. Raindrops hitting bare ground tend to break up the clusters. The soil particles then form a more closely-packed layer that does not soak up water quickly.

Where plants cover the soil, their leaves absorb the impact of raindrops. Therefore, soil clusters remain unbroken, and the large pores in the soil are preserved. Rainwater quickly penetrates it. At a research station in Ohio it was observed that only 0.7 centimeters of water seeped through one bare soil in an hour. By contrast, when the same kind of soil was protected by a layer of straw, 5.6 centimeters of water passed through in an hour—eight times faster.

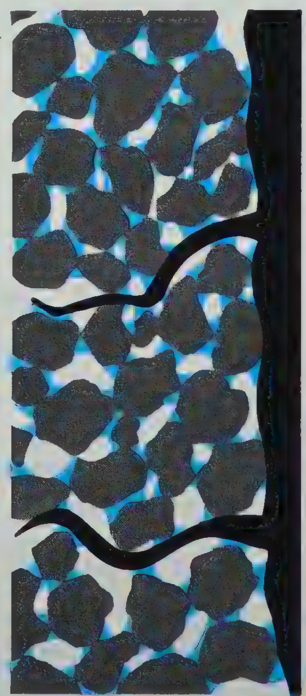
Farmers know the importance of having plant cover when the most intense rainstorms occur. Vegetation on the land, whether on a farm or in the mountains, greatly lessens erosion and flooding. More precipitation enters the soil instead of running off.

In many soils, the mixtures of sand and clay have different-sized openings, like a bag of marbles of varying sizes. The larger openings permit water to move rapidly to lower levels under the pull of gravity. At each point of contact between particles, however, tiny droplets of water are retained by surface tension and by the molecular attraction between the water and solid particles. The water stored in this way is called **capillary water.** Capillary water cannot be drawn down by gravity. It can be removed only by evaporation into the air through soil openings or by absorption into plant roots. (See Figure 8–8.) The supply of capillary water in the upper few feet of soil allows plants to survive long periods between rainfalls. The pores also serve as channels for the circulation of air, which is vital to plant growth.

The amount of capillary water in saturated soil depends on the size of the soil particles. For example, a layer of clay soil 30 centimeters deep will hold about 100 millimeters of capillary water. Thirty centimeters of sandy soil, however, would contain only 25 to 50 millimeters of water when fully saturated.

Clay has smaller pore spaces than sand. The smaller the pore spaces, the higher the capillary water. Thus, clay can store more capillary water and hold it longer than sandy soil. A mixture of sand and clay is a **loam.** Usually loam also contains organic material. Where would grass burn up most quickly during a dry spell: in sand, loam, or clay?

FIGURE 8–8
Capillary water clings to root hairs and particles of soil.



8–5
Water is stored at lower levels.

After a rain, when the pore spaces in the soil contain all the capillary moisture they can hold, additional water filters to lower and lower levels. This is called **gravity water.** At some depth, gravity water accumulates and fills the available pore spaces. The top of this saturated zone is the **water table.** The surface of a lake or river is an exposed part of the water table. Water below the surface of the water table is known as **ground water.** (See Figure 8–9.)

When moisture income is greater than moisture loss (by evaporation and by plants), the water table usually rises. When the water table is higher than nearby streams and valleys, the ground water flows into them. Figure 8–9 shows how this happens.

Streams may be supplied continually by ground water moving into stream channels. During a dry period when there is no incoming moisture, ground water may continue to flow into rivers. In this way the water table is lowered. In desert areas the reverse can happen: the water table is often lower than nearby stream beds. When this happens, water moves from the river into ground water storage, often leaving the stream channel completely dry. (See Figure 8–10.)

FIGURE 8–9
Gravity water seeps down into the ground water zone. What factors might affect the height of the water table?

FIGURE 8–10
Ground water may move into streams. Or streams may supply water to the ground water zone. It depends on the season and the location.

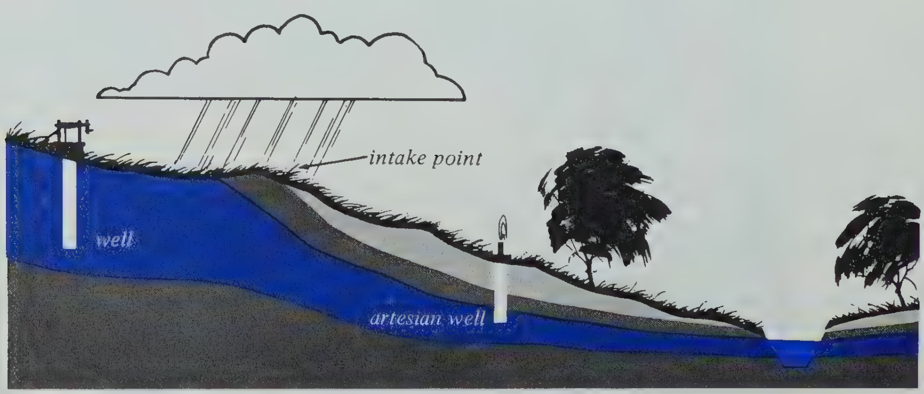
Pore spaces greatly influence the rate at which ground water moves. Ordinarily, ground water flows much more slowly than surface water. Speeds commonly range from about 3 to 30 meters per day. In rare instances, buried channels exist where loose gravel or cracks are found. The ground water flows much more rapidly through these channels than through most earth materials.

Some earth materials transmit and store large amounts of water and are called **aquifers.** Sandstone, for example, usually has abundant pore spaces that may contain air or water. Water seeps into sandstone easily but moves much more slowly through rocks composed of finer particles, such as shale. In igneous and metamorphic rocks, which have low porosities, the number of joints, cracks, and fractures determines the amount of water they can hold.

In many parts of the world, porous rock layers carry water from higher to lower elevations. Where the porous layer is confined by two impermeable layers, an **artesian system** may be created. The impermeable layers act like the walls of a pipe. They prevent the release of the water, and pressure builds up. Wells tapping this aquifer may flow continuously at the surface, provided there is adequate rainfall and the water pressure is great enough. The water pressure depends on the difference in height between the well and the intake point, where water enters the artesian system. (See Figure 8–11.)

Part of the underground moisture remains in storage, part of it moves into rivers on the way back to the ocean, and part of it is used by man. Water may actually be used several times before it returns to the atmosphere or the ocean. For example, in some localities industries are required to pump the water circulated through industrial machinery into the ground to recharge the ground water supply.

FIGURE 8–11
What is the difference between the two wells in this diagram?



On islands and in coastal areas, the ground water may consist of both fresh and salt water. The fresh water, being lighter, floats on top of the salt water. The surface between the fresh and salt water layers rises and falls with the tide, and some mixing occurs. When fresh water is pumped too rapidly, the fresh water table is lowered and salt water can flow into wells. Drainage of low areas near the coast, as well as dredging of tidal waterways, may also cause intrusion of salt water into wells.

Thought and Discussion

1. How does vegetation influence runoff?
2. Distinguish between capillary water and gravity water.
3. How does a river continue to flow during dry spells?
4. What happens to ground water storage during a drought?
5. Should the outlet of an artesian well be higher or lower than the intake area?

Moisture Returns to Air and Sea

8–6
Evaporation and transpiration

You have seen moisture evaporate from wet surfaces when the sun comes out after a rain. Evaporation removes water from swamps, lakes, and wet soils. Vegetation also withdraws water from the root zone of the soil. This moisture is carried through the plants to their leaves, where it changes to vapor and escapes to the atmosphere through leaf openings. This process is known as **transpiration.** Most of the capillary water withdrawn by vegetation is transpired. A very small part is used by plants to build new plant tissue.

ACTION *To see evidence of transpiration, obtain a green potted plant, such as a geranium. Place a plastic bag around the plant so that it is airtight. The following day observe any changes within the bag.*

To record the amount of moisture lost, place two potted plants on a balance, one of them covered with a plastic bag. Balance the plants. The following day record any differences in the adjustment of the balance.

Repeat the action using two cactuses, and explain any differences in the results.

Sometimes a single word, **evapotranspiration,** is used to refer to evaporation *and* transpiration. Evapotranspiration is the only means by which capillary water can be removed from the soil.

Evapotranspiration from the earth's surface is difficult to measure accurately. The water loss from tanks and pans can be measured, but these do not duplicate natural conditions exactly. Some tanks used for estimating water loss contain soil and plants from the area under study.

The amount of water that is added to the tanks can be measured. This gives an estimate of the water that *could* be lost through evaporation and transpiration. The water loss from such tanks depends mainly on air temperature. What other weather factor would be important in determining water loss?

An estimate of the evapotranspiration that could occur with an unlimited supply of water is useful in obtaining the water balance of an area. The water balance or water budget accounts for the income, storage, and loss of water over a region.

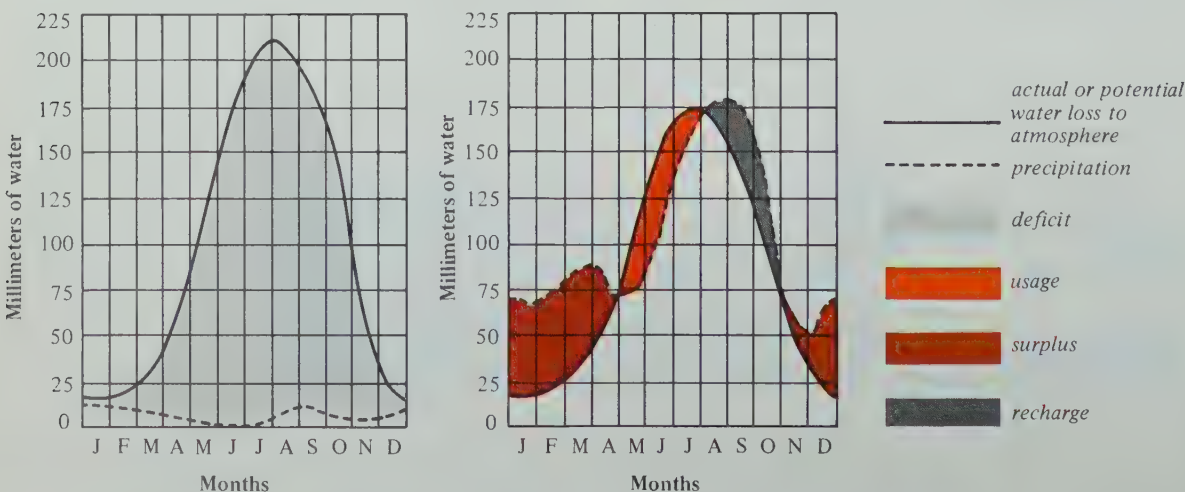
8–7
The water balance

Water budget graphs like those in Figure 8–12 show how the water balance changes during the year. Most places have a surplus of water for part of the year (usually the cool season) and not enough water at another season (usually the warm one). Deserts have a year-round deficit.

Soil moisture usually decreases during the hot months because of high evapotranspiration. Therefore, storage is normally at a minimum at the end of the warm season. (In some regions, like the southern United States, tropical storms in late summer and early autumn cause temporary surpluses of water.) As the sun retreats, moisture income normally begins to exceed water loss to the atmosphere. During the winter, soil and air temperatures are low. Some plants cease to grow, and moisture loss from the ground is slight. In mountainous areas, snow may accumulate.

In late winter and early spring, the melting snow cover releases large quantities of water. The surface layers of soil are soon saturated,

Figure 8–12
Water budget graphs for Yuma, Arizona and Savannah, Georgia. Which graph is from Arizona?



and some of the water flows into the underground aquifers where it is stored. Much of the water from the melting snow joins the surface runoff.

In most humid areas the annual cycle of moisture income and outgo repeats itself in much the same way year after year. Within the larger annual cycle of income, storage, and outgo are a number of smaller cycles that are repeated each time it rains. With the passage of each storm there is a period of soil moisture recharge followed by withdrawal.

Drought or floods are part of the annual pattern of the water balance in many regions. In much of the eastern United States, floods occur each spring. Winter snowmelt and spring rains cover the land in greater amounts than the soil can absorb. Widespread runoff swells rivers beyond their capacity. (See Figure 8–13.)

In most dry or arid regions, long periods of summer drought are the rule. Evaporation increases with summer heat, and rainfall remains low for many months. The occasional thundershower that does come is often so heavy that the water rushes across the land, washing away soil and cutting gullies.

FIGURE 8–13
Flooding of the Arkansas River on June 20, 1965. Normal river flow can be seen at the lower right. Three minutes after this photo was taken, water covered all but the treetops.

8-8
Runoff

The flooding of the Arkansas River (Figure 8–13) followed a series of steady rains. Long after all the soil openings were filled to capacity, rain continued to fall. Water began to collect in streams and flow over the banks, covering many square kilometers of land.

Many intense storms die out before maximum runoff occurs. Look at Figure 8–14. About how many hours after the heaviest rainfall did the greatest runoff occur? There are three reasons for a delay between rainfall and its appearance as streamflow. The earliest rain is captured by the pore spaces in the soil. A second reason for the delay is that it takes time for water to run over the ground and collect downslope in stream channels. Finally, as the water table gradually rises, ground water flows slowly into nearby streams.

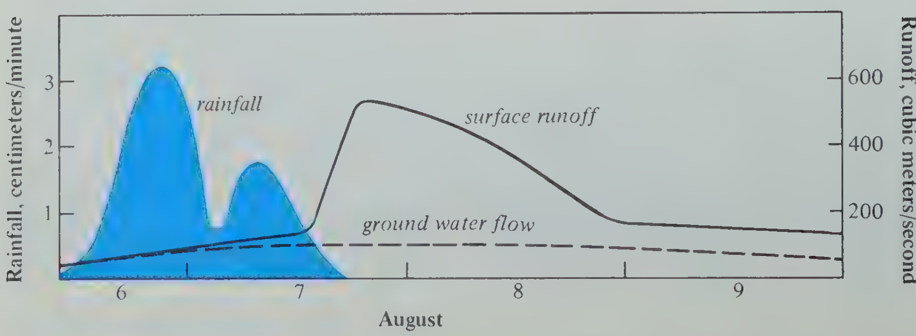
Floods are primarily caused by excess surface runoff. (See Figure 8–14.) However, ground water makes up more than half the annual flow of many rivers. In most rivers, ground water flow regulates streamflow. Storage in swamps, marshes, and lakes also regulates streamflow. Large storage areas such as these can keep the depth of a stream nearly constant. When swamp lands are drained or filled, the runoff and streamflow patterns are changed. Would surface runoff increase or decrease?

8–9
Investigating a flood

In this investigation you will learn how to predict floods using real data. Imagine that in late summer a tropical cyclone crosses the coast, bringing hurricane winds, storm tides, and heavy rains. As the storm moves inland, away from its source of moisture, the wind and rain decrease. Now only a weak low pressure area, the storm changes its course, moving across a mountain range toward the sea. Suddenly, weather radarscopes begin to show rain echoes from towering convective clouds. The observing stations in the path of the storm report very heavy rains. One rainfall station reports 70 centimeters of rain in five hours!

The National Meteorological Center predicts that the storm will pass directly over a river basin that has not had a disastrous flood within the memory of people living there. A quick inspection of weather records shows that the temperature and rainfall during the past month have been about normal.

Figure 8–14
The blue area shows rainfall; the solid black line, runoff. Why don't the curves overlap more?



PROCEDURE

Figure 8–15 contains data that will make it possible for you to estimate the peak of the flood and the time the flood crest will arrive at a town downstream. The data is based on river gauge records from previous storms in the same river basin.

Each person in your group may plot a different graph. In each case draw smooth curves through the plotted points. The four graphs can then be assembled so that your group can discuss the forecast and answer the questions.

*I. Plot the **time** (from the beginning of rain to peak flow) versus the **duration** of the rainstorm. This graph will help you predict when the river will crest and how much time there is to warn the town.*

*II. How high will the water rise? Plot the height of the river versus the **discharge**. The discharge is the amount of water that flows past*

FIGURE 8–15
Data from ten previous storms for Investigation 8–9

I		II		III	IV	
TIME, FROM BEGINNING OF RAIN TO PEAK FLOW, HOURS	DURATION OF STORM, HOURS	RIVER STAGE, m	DISCHARGE $m^3\ sec^{-1}$	DISCHARGE FOR 1 cm OF RUNOFF, $m^3\ sec^{-1}$	STORM RUNOFF, cm (Summer, normal soil moisture)	STORM RAINFALL, cm (Summer, normal soil moisture)
11	5	6.5	3,500	680	0.1	3.3
15	14	6.5	3,700	480	0.5	4.5
21	18	7.2	3,900	410	1.0	3.2
26	18	8.2	4,600	500	1.3	4.0
28	24	9.0	5,000	400	1.3	5.4
29	28	9.7	6,200	300	0.8	6.0
35	31	10.7	7,000	310	3.0	8.0
42	37	11.1	8,200	280	7.0	13.0
46	43	11.8	10,000	230	9.5	16.5
48	49	12.2*	11,600	220	12.7	20.0

* High water mark, record flood to date.

the stream gauging station in the town each second. The flood stage is 10 meters. Draw a line on graph II to represent the flood stage. To determine the height of the flood from the new storm, you will need to know what discharge the storm will produce.

*III. The discharge depends upon the length of the storm. Plot the **discharge for one centimeter of runoff** versus the **duration of the storm.** Remember that this graph only tells you how much discharge can be expected from 1 centimeter of runoff.*

*IV. The total runoff from the storm depends on the amount of rainfall. Plot the **runoff** versus the **rainfall.** The predicted rainfall over the area is 27.5 centimeters. This is more than has ever been recorded in the river basin. You will have to extend the curve on the graph beyond the last two points to estimate the amount of runoff from the predicted rainfall.*

Now assemble the four graphs and answer the following questions:

1. *If the discharge doubles, do you expect the river stage to double?*
2. *What is the proportion of runoff to rainfall for storms of 5 centimeters? 20 centimeters? Why are the proportions different?*
3. *If the weather last month had been hot and dry, would you expect more or less runoff from the storm?*
4. *What is the runoff from the predicted storm rainfall of 27.5 centimeters?*
5. *Assuming the storm lasts for five hours, how much discharge will the 27.5 centimeters of rainfall produce?*
6. *How high will the river rise? You will have to extend the curve in the graph through the last two points to make a flood prediction.*
7. *If the rain begins at 5:00 P.M., when will the flood crest probably occur at the gauging station?*
8. *A sudden, violent flood after a storm is called a **flash flood.** Should you warn the people of the town now about a possible flash flood. Or should you wait until the rainfall reports come in six hours from now?*

8–10
Man changes the water cycle.

Natural changes are always going on in lakes, rivers, and estuaries. For example, heavy rains may erode the land and add sediments to rivers and lakes. In some cases, man's activities speed up these natural changes. The ways people use the land can increase natural erosion. Farm and pasture land usually erode more than land having a natural cover of vegetation. In areas bulldozed for road construction, the rate of erosion may be two thousand times greater than over forested areas. *After the road is built, what can be done to prevent further erosion?*

Without sewage and industrial waste, the natural life cycle of a lake may take thousands of years. In the first stage, the lake may be deep and have little aquatic life. In time, as nutrients and sediments flow into the water, the lake

becomes shallower. It begins to support more plants and animals. The final stage begins as nutrients become abundant. Algae grow into huge blooms. When they decompose, they use up much of the dissolved oxygen in the water, and many aquatic animals die. In time, the lake becomes a swamp and finally a land area. This aging process is known as **eutrophication** (you-*trowf*-i-KAY-shun).

Wastes from industrial, municipal, and agricultural sources may speed up the life cycle of lakes. Nutrients from the sewage speed up the eutrophication of lakes and rivers by fertilizing the plant life. Heat introduced into the water from power plants may also cause changes in the aquatic life and speed up the growth of algae.

As the plants increase and more organic matter decomposes, the oxygen in lakes and ponds may be depleted. When all the oxygen is used, the bacteria that do not require oxygen begin to thrive. These produce hydrogen sulfide. The lake or river turns dark and gives off foul odors.

Mixing in the hydrosphere is not nearly as effective as in the atmosphere. Water pollution is much longer lasting than air pollution. Sometimes the processes set in motion—like the rapid aging—cannot be reversed, without immense amounts of energy and money.

Thought and Discussion

1. Runoff takes place over the surface of the soil and also as ground water flow. What would you consider the most accurate way to measure the runoff from a river basin?
2. The seeding of clouds that are already overhead is a possible method of controlling the runoff cycle. If it were possible to produce precipitation reliably by this means, would it speed up the runoff cycle?

Unsolved Problems

The distribution of the world's fresh water often does not match human needs. We have not yet found ways to overcome water shortages (or population excesses) at reasonable cost. The problem has been approached in many ways: cloud seeding to produce rainfall, extracting fresh water from sea water, decreasing evaporation from reservoirs, building reservoirs to hold seasonal excesses, transferring water from one basin to another, more efficient use of water, keeping existing rivers pure, and planting types of vegetation that will hold back runoff and produce a more even flow of water. It has even been suggested that coastal cities might acquire water by towing icebergs from polar regions and melting them. Some of these proposals work well in certain local areas, but none offers a complete solution.

Seeding clouds and desalting sea water involve the direct transfer of water to the land from other storage systems in the water cycle —the atmosphere and the ocean. They are sort of "short circuits." The other methods are concerned with conserving water by changing the amount, location, and flow of water after it has reached the land.

Chapter Review

Summary

Although more precipitation falls on the ocean than on the land, water on the land is an important part of the water cycle. Water on the land can be considered in terms of income, storage, and loss. Precipitation is the main source of water on the land. The amount of rain and snowfall varies widely and depends on the season and geographic location.

Water reaching the land may be stored in snowfields, ice caps, lakes, and streams. It may be stored in the soil as capillary water in the root zone or as ground water at lower levels. Water is removed from the land largely by evaporation and transpiration. Two-thirds of the precipitation falling on the continents goes back into the atmosphere by this means. The other third leaves the land as runoff in surface streams and ground water.

In adjusting to his environment and altering it for his convenience, man sometimes changes the patterns of water on the land. The effects of such changes on local weather and climate have not been thoroughly investigated. However, poor use of water and land causes many undesirable changes in lakes, rivers, and estuaries. These changes endanger man's supply of fresh water.

Questions and Problems

A

1. What is the earth's main source of fresh water?
2. During what season of the year does the most precipitation fall?
3. What happens to the precipitation that falls on the earth?
4. What is a pore space in soil?
5. How is water held in soil?
6. How is bedrock able to store ground water?
7. How is water that falls on the land returned to the ocean?
8. Where does the heat come from when water is evaporated or transpired?
9. In which season of the year are evaporation and transpiration highest?

B

1. How do plants protect the soil?
2. What is the ground water table?
3. What is an aquifer?
4. How does an artesian system work?
5. Why isn't there much runoff when it first begins to rain?
6. What factors govern the rate of penetration of water into the ground? In addition to those mentioned in the text, can you think of any others?

C

1. During humid periods in the spring, water condenses on snow surfaces. What effect does this have on the rate of melting? Do you think that this is a factor in spring floods?
2. Can ground water flow uphill? Explain your answer.
3. Do you think that large streams or small streams would vary more during and after a rain?

4. Would water evaporate faster from a pan of hot water or a pan of cold water? Do you think that there is any difference in the rates of evaporation from large deep lakes and small shallow lakes?
5. Is perspiration in humans related to transpiration in plants? What is the main function of each process?
6. Are evaporation pans a good way to measure the loss of moisture from a region? Explain your answer.

Suggested Readings

Bauer, Helen, *Water: Riches or Ruin*. Doubleday & Company, Inc., Garden City, N.Y., 1959.

Cocannouer, Joseph A., *Water and the Cycle of Life*. The Devin-Adair Co., New York, 1958.

Davis, Kenneth, and Day, John A., *Water: The Mirror of Science*. Time, Inc. (Life Science Library), New York, 1966.

unit three

The Rock Cycle

9. The Land Wears Away

In a cemetery in Massachusetts a tourist stoops to read a tombstone. Its message has been all but erased by the action of the weather.

The captain of an ore boat steering across Lake Superior retraces the paths of the ice age glaciers that scooped the lake basin out of soil and rock.

Other changing landscapes: A mud-red stream slices its way across Arizona carrying away silt and sand leaving a canyon behind. In Peru in 1970 an earthquake starts an avalanche. It roars down a mountainside burying 20,000 villagers beneath tons of rock and mud.

Weathering, glacial ice, running water, and landslides have been shaping earth's face for billions of years. Regardless of which "tool" nature uses or how fast it works, the end result is always the same: some parts of the land are gradually worn away.

Rocks Break Down in a New Environment

9–1
Weathering changes rocks.

Most rocks formed deep within the crust. The environment there is different than at the earth's surface. Temperature and pressure increase with depth in the earth's crust, but air and water decrease. When rocks at the surface are exposed to air and water, they break down. This process of breaking down rocks is called **weathering.** It occurs not only at the earth's surface but also at any depth penetrated by air and water.

Although rock fragments, sand, and mud are produced by weathering, the process is not merely destructive. The rocks are destroyed, but the matter they contain is not. New minerals can be formed in a weathering environment. More important, when rocks are sufficiently weathered, they are reduced to soil. If rocks were not destroyed to create soil, there would be no life as we know it today.

Geologists recognize two types of weathering processes: physical and chemical. Physical processes make small rocks out of big ones without changing the minerals in the rock. (See Figure 9–1.) This change is called **disintegration.**

Because water is a common liquid that expands when frozen, it is the main agent of disintegration. When water freezes in the cracks of rocks, it expands, forcing the rocks to break apart. In the mountains, where water repeatedly freezes and thaws, the expanding ice pries the rocks apart, and disintegration may be rapid. The rocks in Figure 9–2 were separated and broken by growing tree roots. As the tree grew, its roots became larger, acting as a lever to pry the rocks farther apart. Water could then seep farther into the cracks.

Chemical weathering, or **decomposition,** is a slow but continuous process. The minerals in chemically weathered rocks are converted into new and often more valuable products such as soil. Certain minerals in a rock are dissolved more readily than others. When these minerals dissolve, pits and cracks are left behind. In time, the remaining material may become a skeleton of the original rock. Such rocks are usually soft and easily broken apart.

Since decomposition occurs on mineral surfaces, it is aided by disintegration. When a rock is weathered into small particles, the total surface area can increase thousands of times. (How much will the surface area increase if a cube, one centimeter on each edge, is cut into eight equal parts as shown in Figure 9–3?) The two weathering processes cooperate. Breaking up rocks exposes new surfaces and speeds up chemical weathering. In turn, decomposed rocks break up more easily.

9–2
Water—the universal solvent

In Chapter 2 you learned that the dipolar nature of the water molecule accounts for its unusual dissolving power. Dissolving removes ions from minerals in rocks, causing their chemical breakdown. A compound like sodium chloride (halite) dissolves readily in water. Because most materials do not dissolve as readily as halite, chemical weathering works slowly.

FIGURE 9–1
This rock was uplifted. Erosion then reduced the pressure on the underlying bedrock. The bedrock expanded, producing cracks and breaks. Will these cracks affect further weathering?

FIGURE 9–2
How can tree roots help weather rocks?

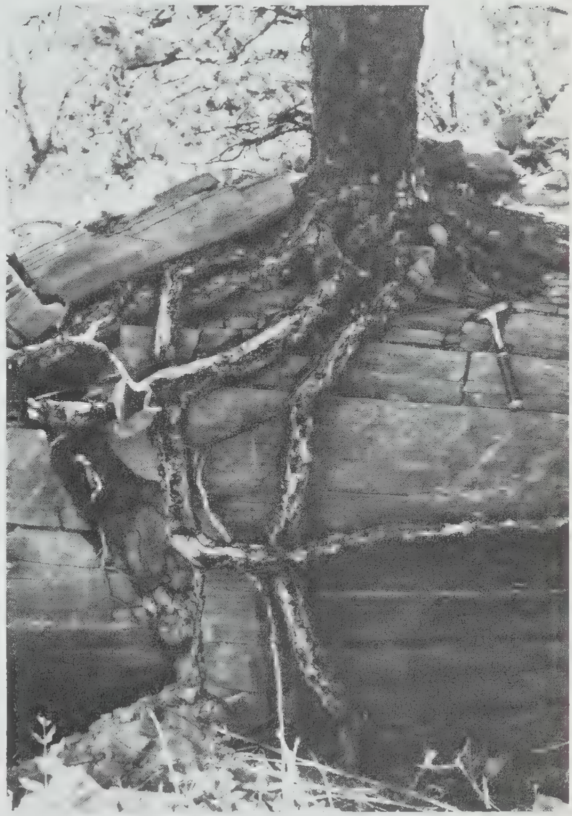
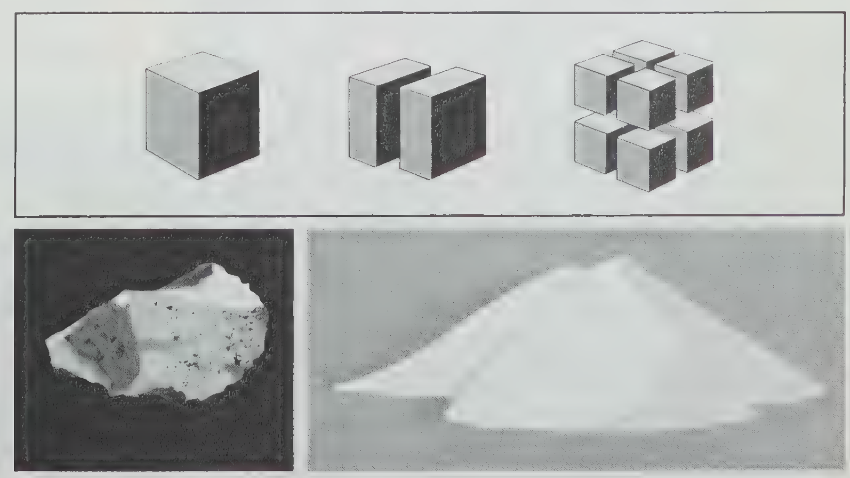


FIGURE 9–3
Dividing an object creates new surface areas.



Water alone is a powerful solvent. The addition of other chemicals such as oxygen and carbon dioxide make it even stronger. Oxygen from the air dissolves easily in a film of water surrounding rock particles in the ground. The oxygen can then combine with iron atoms exposed by the weathering of olivine. Rust (iron oxide) is formed. This oxide can exist as a coating or stain on mineral grains. Iron staining is a common cause of color in rock exposures. Some iron stains are yellow or red; others are blue-gray. The color depends on the ratio of iron to oxygen in the rust.

ACTION *Moisten some steel wool and wrap it in plastic or place it in a closed container so it will not dry out. Observe the steel wool for several days. What changes do you see? What has been formed? Is the "weathered" steel wool easier to break than the original steel wool? Is this an example of chemical or physical weathering?*

As the living cells of all plants and animals use oxygen, carbon dioxide is given off. You know that carbon dioxide dissolves in water since it is found in every carbonated drink. Some of it forms carbonic acid (H_2CO_3) in the water. This is more effective than pure water in dissolving certain ions such as calcium and potassium. The calcium and potassium ions may then be absorbed through the roots and used for plant growth. (See Figure 9–4.)

The lichen (LY-ken) growing on exposed rock in Figure 9–5 releases carbon dioxide on the rock surface. The surface weathers and allows the lichen to grow where other plants cannot survive because of the absence of soil. Weathered debris and organic matter accumulate and support other types of vegetation.

The remains of dead plants and animals may be decomposed by microscopic organisms like bacteria, molds, and funguses. Dead plant and animal debris is eventually reduced to fine particles that adhere to mineral grains and darken them. Only a small per cent of organic matter is needed to color soil black or dark brown.

The large cavern shown in Figure 9–6 formed because limestone dissolves readily in carbonic

FIGURE 9–4
Roots give off carbon dioxide. It dissolves in water, and carbonic acid is formed. Carbonic acid speeds up chemical weathering.

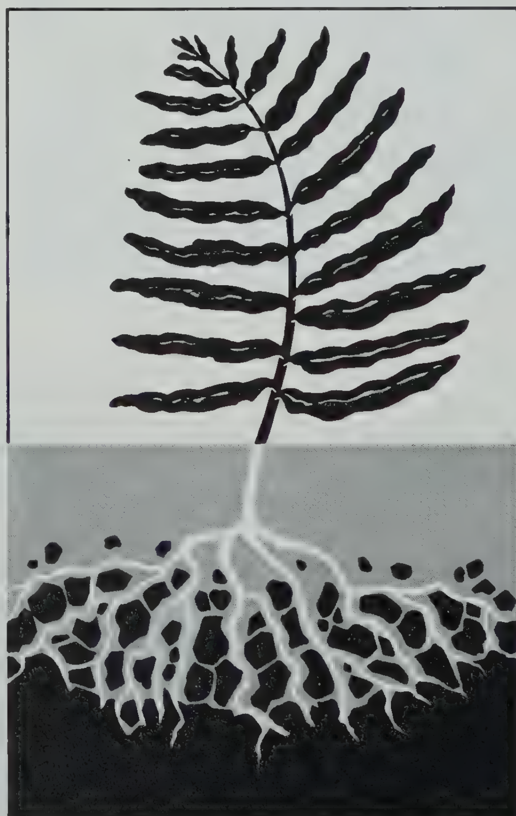


FIGURE 9–5
Lichens are the first plants to grow on exposed rocks when weathering begins. Lichens can exist with very little moisture for years at a time.

FIGURE 9–6
Carbonic acid dissolved in water carved this limestone cavern. The deposits on the roof of the cavern are called stalactites. The deposits on the floor are stalagmites.

acid. The removal of soluble materials by water percolating through rocks and soil is called **leaching.** Materials leached from one location can form new minerals at another location. Thus, the dissolved limestone may be deposited on the roof of a cavern to form stalactites.

9–3
Investigating products of weathering

Although we consider granite to be a most durable rock, much soil has been produced by the weathering of granitic rocks. Various minerals in granite weather at different rates. Quartz resists weathering. Mica is less resistant, and feldspar the least resistant. Minerals that weather slowly remain as rock fragments; those that weather rapidly form colloids and ions. ***Colloids*** *are particles small enough to remain suspended in water for a long time. Ions and colloidal particles are more easily washed away than rock fragments.*

Aluminum and silicon, released from minerals during weathering, can combine with oxygen to form a group of silicates called ***clay minerals.*** *These minerals are frequently colloidal in size. The formation of clay minerals in soil is one example of the creative aspect of weathering. The weathering process might be compared to wrecking a building and using the pieces to build a new structure. In this investigation you will examine those products of weathering that remain after ions and colloids are washed or blown away.*

PROCEDURE

Examine the granite and the two soil layers provided for you.

1. *In what ways are they similar? How are they different?*
2. *Can you identify a mineral that exists in both the granite and the two soil layers?*

Put a half teaspoonful of each material in a test tube with water. Shake the test tubes and let the materials settle. Discuss the results. The soil layers you examined were formed from granite.

3. *Which of the two soil samples was taken from the top layer?*

Thought and Discussion

1. Why do rocks weather?
2. How does physical weathering aid in chemical weathering?
3. How is carbonic acid produced and how does it affect weathering?
4. Why are many earth materials red in color? What element commonly produces color in earth materials?

Soil—A Basic Earth Material

9–4
How soils develop

Rock weathering produces the life-supporting layer on the earth's surface called soil. Soil is

the link between solid rock and the world of living things. Although some plants such as lichens can grow on bare rock, most plants need soil to survive.

Physical and chemical weathering continues as soil forms. Vertical layers, sometimes called **horizons,** develop in the rock debris. The boundary between horizons is not usually distinct. A soil with only a few horizons is called an **immature soil;** one with many layers is called a **mature soil.** (All the layers in a particular soil make up the **soil profile.**)

After rock debris begins to accumulate, the first important change is the addition of growing plants. Plants assist the weathering processes and also slow down the removal of soil by wind and water. The soil that remains in place becomes thicker with time.

When plants die, they decompose. The decaying remains form **humus.** Humus is the primary source of the nitrogen needed for new plant growth. Humus collects in the uppermost layer of soil, called the **topsoil.**

In an immature soil, the topsoil lies directly on top of the solid rock, or **bedrock.** A mature soil has another horizon separating the topsoil (A horizon) from the rock debris (C horizon). (See Figure 9–7.) The A and B horizons are made up of several layers.

The middle or B horizon is called the **subsoil.** As water seeps through the topsoil, some minerals are dissolved. Other materials, particularly fine particles of clay and iron oxide, are carried downward suspended in the water. These smaller particles are deposited in the subsoil.

The higher clay content makes the subsoil harder to plow than the topsoil. Clay particles also block the pores in soil, making it more difficult for air, water, and roots to penetrate. However, a certain amount of clay is necessary to "cement" the soil together. Also, the negatively charged clay particles attract and store positive ions of calcium, magnesium, and potassium. Many plants thrive in soils, called **alkaline soils,** that are rich in these elements.

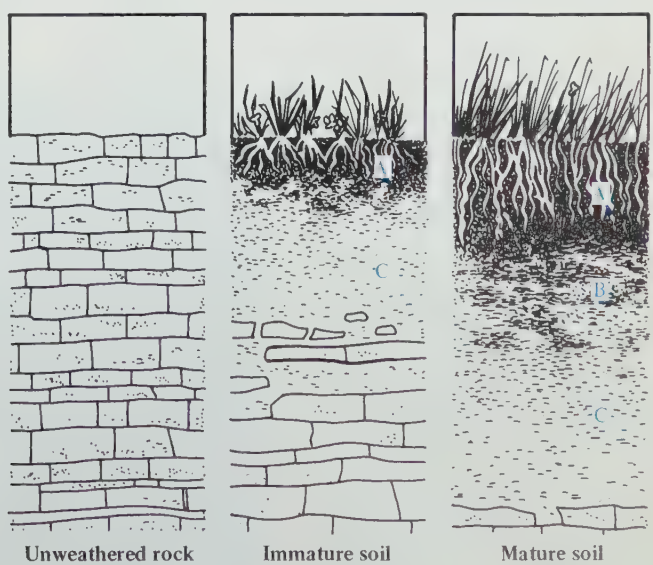


Figure 9–7
Stages in the development of a mature soil. What factors could affect the time it takes to develop a mature soil?

9–5 Factors that influence soil formation

Of all the influences on soil formation, climate is the most important. Eugene Hilgard, an American geologist, found that a given climate produced similar kinds of mature soils from a variety of bedrocks. In warm moist climates, rocks decompose in a relatively short time. There is usually a rapid chemical breakdown, hastened by abundant plant and animal life.

Much different climatic conditions exist in deserts. There is little rainfall, the air is dry and hot, and bedrock wears away more slowly. In temperate regions there are strong seasonal variations in climate. The rocks weather by a combination of processes. Frost action is dominant in winter. Heat, rainfall, and leaching by ground water are more effective in summer, spring, and fall.

Because of the importance of climate, the broad soil regions of the world follow the distribution of climates. Even so, soils and climatic zones are not always identical. Climate is only one of the factors that control the development of soil. Other factors are the type of bedrock, time, the topography, and living organisms.

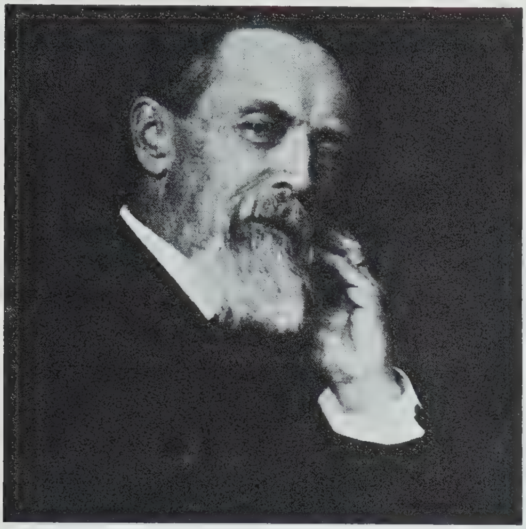
The minerals in rocks react differently to weathering forces. For example, quartz is a very resistant mineral. When it finally does disintegrate, it forms sand and silt. It supplies no clay to the soil and no plant nutrients. Most rocks are mixtures of minerals, few of them as resistant as quartz.

The original bedrock from which a soil forms is called **parent rock.** Soils like children do not always resemble their parents. This is particularly true of older soils. Soils normally develop very slowly. In some areas, a mature soil takes thousands of years to develop. Mature soils usually form on gently sloping lands with good drainage.

Immature soils can be found on steep slopes where the upper soil layer is almost continuously worn away. They also occur in regions that are flooded regularly. New material is deposited with each flood and the horizons never get a chance to mature. Poor foresting or farming practices, which allow topsoil to be worn away, also prevent the formation of mature soils.

FIGURE 9–8
This land in the Black Hills is used for grazing. How could overgrazing cause erosion?

EUGENE W. HILGARD



Before the nineteenth century, scientists had given little attention to the study of soils. One of the first men to increase the productivity of American agriculture through the study of soils was Eugene W. Hilgard (1833–1916).

Hilgard, a geology professor at the University of California, established one of the nation's first agricultural experiment stations in 1874. He appears to have been the first scientist to recognize that soil was divided into distinctive layers.

Hilgard's pioneer work resulted in his book *Soils*, which is still used today. He noted that the soil profile that developed in a region was related to both climate and vegetation. In addition, he recognized the importance of rainfall and temperature in turning bedrock into soil. Hilgard also observed that climate controlled leaching, the type and degree of plant growth, the development of clay, and the accumulation of organic matter.

From these observations Hilgard concluded that many ancient peoples lived near deserts because rich soils developed there. He believed that these people found irrigation of fertile deserts easier than supplying plant nutrients to less fertile soils in humid regions.

9–6 Kinds of soils

None of the five factors of soil formation is constant over the entire earth. Because of the wide variation, there are hundreds of thousands of possible combinations of factors and possible local soil types. To sensibly study soils, we must group similar local types into broader categories.

Figure 9–9 on the next page is the distribution of the major soil types in North America. What type of soil is typical of your part of the country?

Mountain soils (Figure 9–10) are usually stony and thin. The slopes are too steep to allow the formation of a mature profile. Pockets of other soil types are often found in regions of mountain soil.

Forests generally occur in regions of high rainfall. The intense leaching produces a soil low in certain nutrients, especially calcium and magnesium. Such a soil is **acidic**. Pine, hemlock, and spruce require little calcium and

magnesium and therefore thrive in acidic soil. Falling leaves and needles provide most of the organic matter in the forest. When they decay, a thin topsoil forms.

Trees can grow in leached soil because their roots penetrate deep into the ground and because they mature very slowly. A plant that matures in one season requires a more fertile soil. As strange as it seems, the lush rain forest in Figure 9–11 is supported on a foundation of impoverished soil. Little light penetrates to the forest floor. Therefore, few green plants grow there, and little humus accumulates. People sometimes suggest that jungles ought to be cultivated to increase the world's food supply. But a few years under cultivation would completely strip a forest soil of the little plant nourishment it can provide.

When not abused, grassland soils are more fertile than forest soils. The topsoil is thick and rich in humus from the decay of grass stems. In the United States, wheat is grown and cattle are grazed on the grasslands.

Prairie soils are a form in between grassland and forest soils. Prairie soils resemble grassland soils because they have a deep topsoil rich in humus. But they also have the high rainfall typical of forests. This unique combination makes them naturally fertile and very productive. Most of the "Corn Belt" in the United States contains prairie soil.

Desert soils are very rich in minerals. Because of the shortage of moisture, they are only slightly weathered or leached. The lack of rainfall also limits plant growth. Thus, the soil is low in nitrogen and humus. Nevertheless, some plants, such as cactus and mesquite (Figure 9–12) can exist in this poor soil.

With proper irrigation, a desert soil can be fertile (Figure 9–13). But irrigation is tricky.

FIGURE 9–9
The distribution of major soil types in North America. This map is very general. These soil types can be subdivided into numerous local varieties.

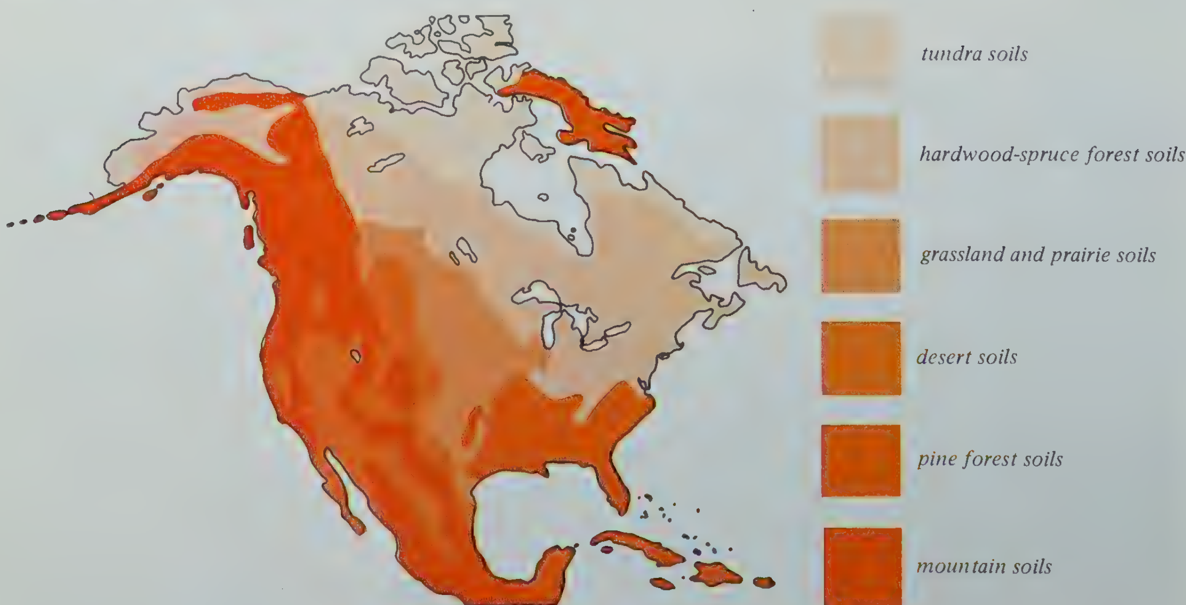
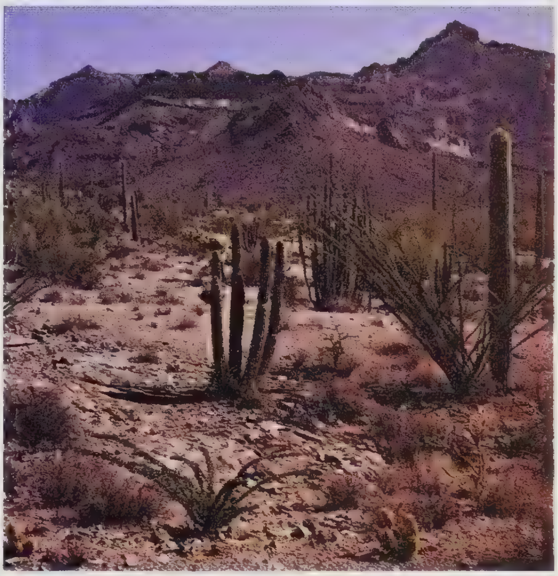


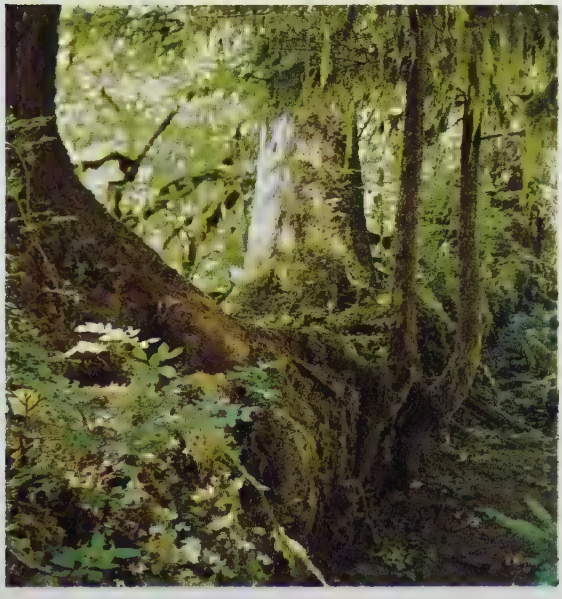
Figure 9–10
How would mountain soil differ from soil in warm, humid areas?

Figure 9–11
Rain forest soil cannot support intensive farming.

Figure 9–12
What features of cactuses help them to survive in the desert?

Figure 9–13
Irrigation has turned this desert in Utah into productive farmland.





If the water is allowed to stand and evaporate, it deposits the salts that it carried in solution. The soil can become too salty to grow anything. In recent years, parts of California's rich Imperial Valley suffered this fate.

ACTION *With the help of your teacher, select a site where you can examine an entire soil profile. Avoid locations near construction sites or where there is frequent flooding. You might want to compare two locations, for example one at the top and one at the bottom of a hill.*

You should wear old clothes and bring along a shovel, a ruler, small paper bags for samples, and a pencil and notebook. You will probably have to dig down about one or two meters before you reach parent material.

After you expose the profile, make a sketch of the horizons. Record the depth of each horizon and take a soil sample from each layer. Back home or at school you can compare the color, texture, and porosity of the layers. Is your profile mature or immature? Is it more typical of forest, grassland, or desert soil? Are the boundaries between horizons sharp?

In some parts of Alaska the combination of low temperatures, slight rainfall, and slow evaporation produces **tundra** soil (Figure 9–14). These regions are so cold that the deeper layers of soil remain permanently frozen. (They are known as **permafrost.**) The upper soil layer thaws, but has poor drainage during the summer. This water-saturated soil is black from slowly decaying humus.

FIGURE 9–14
Tundra soil and exposed permafrost. Vegetation grows on tundra soil. But the species are usually "dwarf" varieties because of the short growing season.

FIGURE 9–16

Thought and Discussion

1. How does subsoil differ from topsoil?
2. What is the difference between mature and immature soils?
3. In what type of climate would you expect rock weathering to be most complete?

Erosion—Products of Weathering Move Downhill

9–7
Investigating stream erosion

How are the streams in Figure 9–15 different? Which one contains more water? Which one has a greater slope? Both stream slope and stream volume affect erosion. In this investigation you will see how.

PROCEDURE

Using the equipment shown in Figure 9–16, put 50 milliliters of gravelly sand in the trough. Erode the material from the trough with running water. Vary the stream slope and stream volume to help you answer the following questions:

1. *How does stream slope affect the rate of erosion?*
2. *How does stream volume affect it?*
3. *How did the different sizes and shapes of the particles affect their movement?*
4. *How could stream volume and stream slope change in nature?*

FIGURE 9–15
Which of these streams would carry the most sediment?

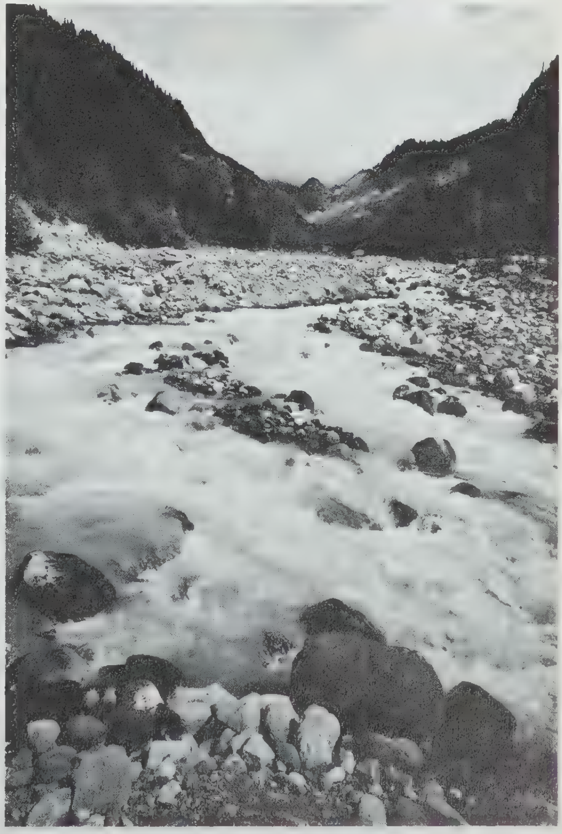


FIGURE 9–17
This landscape in Arches National Monument in Utah is called the Three Gossips. What agents might have worn away land here?

FIGURE 9–18
The 1959 Yellowstone Earthquake caused this landslide.

FIGURE 9–19
What evidence of creep can you see here? What do creep and landslides have in common? How do they differ?

9–8
Gravity—the force behind erosion

Suppose the products of weathering had collected where they developed for the billions of years since the earth formed. How would the earth's surface differ from what you now see? What evidence is there is Figure 9–17 that loose weathered material was removed?

Erosion is the movement of rock and soil particles from one place to another. Every object on earth tries to move toward the center of the earth. The force pulling objects downhill is gravity. Geologic agents such as water, ice, and winds are agents of gravity.

A boulder in Figure 9–17 can roll downhill. If the boulder does not roll all the way to the sea, it will have the potential to fall again. While it is moving, the boulder erodes itself and other objects in its path. The greater the distance that the boulder falls, the greater its speed and the more damage it causes.

During landslides loose material moves rapidly downhill. (See Figure 9–18.) The slower shifting of material in Figure 9–19 is called **creep.** Water between the soil particles helps them slide downhill. Alternate freezing and thawing can also help this movement. Not all materials move as noticeably as a landslide. But a tremendous amount of individual sand and soil particles gradually move downslope each day.

Water vapor carried to high elevations by the air eventually ends up as water flowing down over the slopes into stream channels. In the stream valley in Figure 9–20, the erosion is taking place mainly on the valley slopes. The stream is like a conveyor belt that carries away the material from the valley walls.

Gravity also controls the geologic work of ice and wind. Can you explain how?

9–9
Water, ice, and wind erode the land.

The action of water, wind, and ice wears down the land and transports loose earth material from the land to the sea. The journey for most mineral and rock particles is long and winding. A particle carried by a glacier might stay in one place for thousands of years before it is moved along again by a stream. This process of transportation and deposition may be repeated many times before material loosened from a mountain side eventually reaches the sea.

FIGURE 9–20
Running water and gravity move eroded material to the stream valley. The stream is a conveyor belt to the sea for the products of erosion.

Soil may be thought of as a temporary deposit of weathered material. The amount of soil now on the land is the difference between the amount produced by weathering and the amount removed by erosion. (Why are soils commonly found in mountains thin and rocky?)

After an intense rainstorm, a field without a protective vegetative cover might appear as shown in Figure 9–21. The eroded material eventually washes or caves into streams.

All streams carry an invisible load of ions in solution. The size of this chemical load depends on the kind of rock and soil in the area that feeds the stream. These ions are transported along with suspended particles and eventually reach the sea.

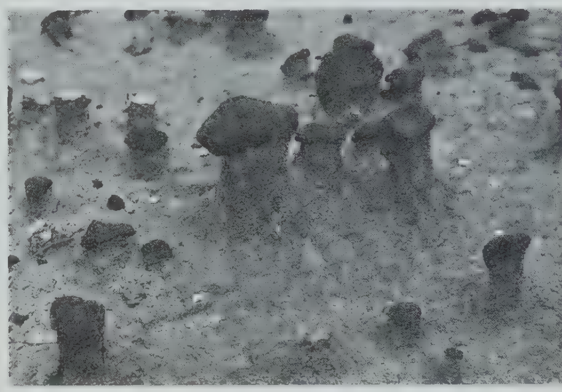
Particles of minerals and rocks that are suspended in a stream muddy it. In a large river, this visible load of sediment may be tremendous. The Mississippi River, for example, carries about two million tons of sediment to the Gulf of Mexico each day.

Not all of the sediments carried by a stream are suspended in the water. Larger fragments are rolled or bounced along the bottom as shown in Figure 9–22. When the rock fragments strike other particles or the solid stream bed, they break into smaller pieces that can be carried even farther. The particles are like tools, breaking and grinding each other and the surfaces of other rocks.

A stream's capacity to erode or to deposit material may change. During floods a stream can carry more material and larger particles than usual. As flood waters recede and velocity decreases, the larger particles begin to settle out. Next, sand settles to the stream bed where

FIGURE 9–21
a. *The effect of a severe rainstorm on unprotected soil. Note the pinnacles of soil that were protected by stones.*
b. *The impact of a raindrop*

a.



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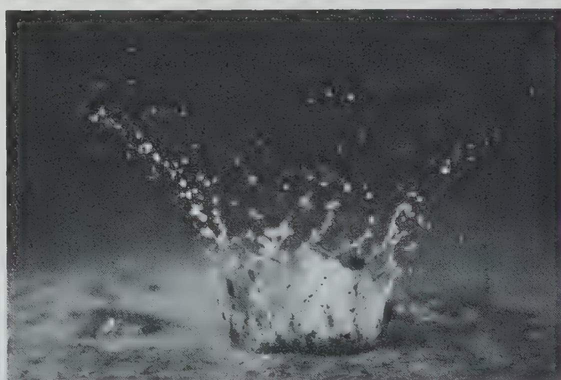
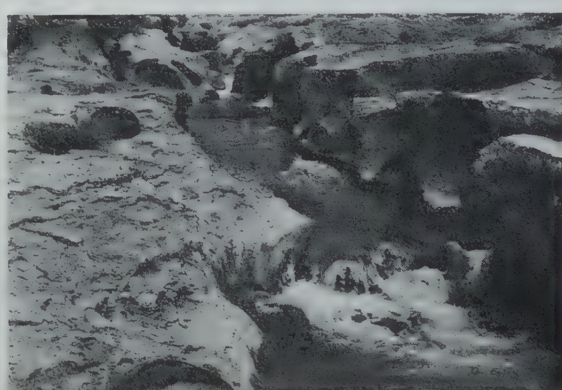


FIGURE 9–22
Coarse sand and gravel carved the holes in the rock walls of this stream.



it may be dragged along the bottom. Finally, only fine silt and clay remain suspended in the water. If the velocity decreases still more, some of these fine particles will be deposited. Since velocity can also vary along the length of a stream, the stream can erode material in some places and deposit it in others.

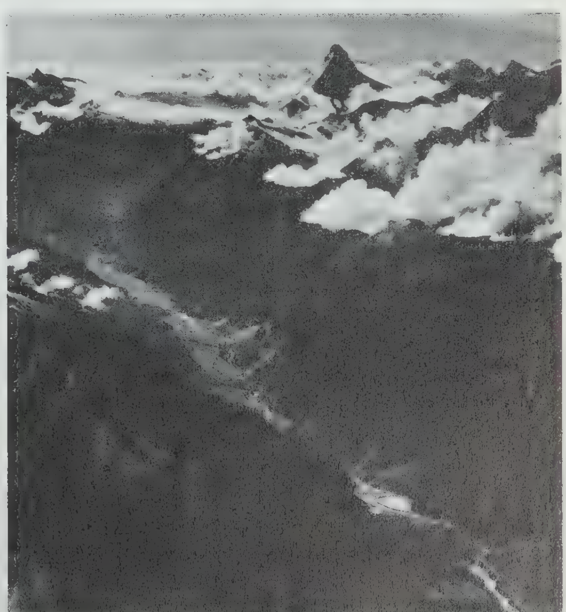
Glaciers are another agent of erosion. Glacial ice flowing slowly downhill can pick up a load of boulders and pebbles in its path. Rocks falling on its surface add to the load. These boulders act like grains in a giant piece of sandpaper, scratching and grooving other rocks. (See Figure 9–23.) A mass of moving ice and

FIGURE 9–23
a. *Closeup of a glacier showing bands of rock debris.*
b., c. *Which of these valleys was changed by a glacier?*

a.

b.

c.



broken rock debris is a slow but effective erosional agent.

Wind must have a much greater velocity than water to move particles of the same size. Fine materials like silt and clay-sized particles are easily lifted by winds. Because wind usually cannot carry large particles, it sorts material by size. The pebbles and boulders that are left behind produce a rough, rocky surface. If there is a large supply of sand, dunes are formed where the wind loses energy and drops its load. The sand dunes in Figure 9–24 appear to be stationary. They are actually in constant motion because the grains roll over each other on the surface of the dunes.

During periods of extreme drought, wind erosion may strip the land of fertile topsoil. The barren wind-swept landscape in Figure 9–25 is a typical "dust bowl" caused by wind erosion.

9–10
The magnitude of erosion

The major agent of erosion is the water that falls on and runs off the land. Rainfall is most important in shaping landscapes, even in deserts. For example, the scene in Figure 9–26 is part of Death Valley where the average rainfall is less than five centimeters a year. In some years there is no rain at all. Yet running water still has done much to shape the desert landscape.

The average total precipitation on all land areas each year is at least 125,000 cubic kilometers. Some of it falls gently as snow, but most of it lands as raindrops. Large drops can splash sand grains 30 centimeters or more into the air. On land unprotected by vegetation,

Figure 9–24
Sand dunes in Death Valley.

Figure 9–25
A "dust bowl" in Colorado. How could this landscape have been prevented?

Figure 9–26
Even in the desert, water is the most important agent of erosion.

raindrops alone move particles downslope. About 75 per cent of the total precipitation is either evaporated or retained in rocks and soil. The remaining 300,000 cubic kilometers runs off the lands into the oceans. The capacity of this torrent to erode land is greater than all other agents of erosion combined. (Ocean waves also erode the land, but only in a narrow band along the shores of continents.)

In the United States, stream-gauging stations regularly are used to measure the load of suspended sediment. The materials carried in solution and dragged along the stream bed are also measured. When the total load of the stream is compared to the area of the land that the stream drains, it is possible to calculate the total amount of land removed. This amount ranges from less than 40 to over 2,000 tons per square kilometer per year. At this rate, it is estimated that all the land now above sea level could be leveled in about 12 million years. However, this is unlikely because other earth processes work to uplift portions of the crust.

Although glaciers can transport tremendous amounts of material, they are not a major leveling agent today. Large valley glaciers carved the spectacular landscape in Yosemite National Park. Still larger sheets of ice scooped out the basins occupied by the Great Lakes. Today, however, glaciers cover only about 10 per cent of the land area of the world, mainly in Antarctica and Greenland. Even during the ice ages, glaciers covered only about 30 per cent of the land.

Wind is a minor erosional agent. On land, wind continually redistributes fine particles without necessarily carrying them to lower elevations. In arid regions it may shift loose sand around, forming dunes, and making the land less level than before.

Wind blowing in from the sea can actually move material from the beaches inland, building dunes and thereby returning sediment to the land. On some unprotected shores, such as parts of Cape Cod, sand is blown directly out to sea. This is the only example of net erosion by wind alone. Although the wind plays a small part in eroding the land, its delicate sculpturing can create beautiful landscapes. (See Figure 9–27.)

Thought and Discussion

1. What are the causes of erosion?
2. How are particles moved by each agent of erosion?
3. What is a "dust bowl"? How does it develop?
4. How does erosion by glaciers differ from erosion by streams?

Figure 9–27
The King's Men in the Valley of the Goblins in Utah. What erosional agent has been at work here?

Unsolved Problems

Man plays a significant role in the ageless battle between the materials of the earth and ice, wind, water, and gravity. Some projects, such as flood controls, reduce erosion. More often, overfarming, overgrazing, and strip mining have exposed the soil to wind and water. We need to protect the soil if it is to continue to support life. A global concern should be solving erosion problems and attempting to conserve our precious soil.

Man is extending his explorations onto the sea floor. Do processes that shape the land like weathering and erosion also operate under the sea? How do they differ from those that occur on land?

Chapter Review

Summary

The process that physically and chemically breaks down rocks is called weathering. The variety of minerals in the rock and the type of environment determine the rate of weathering.

If the loose rock fragments remain in place, soils may eventually develop. In time, these products of weathering are changed into mature soils whose structure depends on the climate and vegetation of the area. If the rock fragments are transported, resistant minerals become separated from those that weather easily.

Gravity exerts a constant force to move material to lower elevations. Gravity moves material slowly by creep and rapidly during landslides. Water, ice, and wind move materials long distances. Of these three, running water is the most effective agent.

Most eroded rock winds up in the sea, but the route is long and full of detours. Particles are moved, deposited, picked up again, and redeposited many times before they reach the ocean. Weathering, soil formation, and erosion operate together to wear away the land.

Questions and Problems

A

1. What happens to rocks that are exposed to air and water?
2. Why is water such an important factor in weathering?
3. How does weathering of rocks and minerals contribute to man's well-being?
4. What are the products of the weathering of granite?
5. How do mature desert soils differ from soils of forest regions?
6. What is the role of gravity in erosion?
7. How are materials moved by streams?
8. Why is water able to transport larger particles than wind? Why can ice transport larger particles than water?

B

1. Why are almost all the sand particles in the dunes around the Great Lakes and on the beaches of New England composed of quartz?
2. Colloids slow down the removal of calcium from the soil by percolating water. Why is this process important for the growth of vegetation?

3. A limestone contains 10 per cent impurities, including some insoluble clay minerals. If this limestone weathers at the rate of 30 centimeters in a thousand years, how many years would be required to form 1.5 meters of soil?
4. Compare the velocity of a stream to the amount of dissolved chemicals the stream carries.
5. How would you establish whether the soils in your area were formed from bedrock or sediment?
6. What evidence would establish that the loose material at a given location was a glacial deposit?
7. How could you tell whether a stream valley in the mountains was formed chiefly by a glacier or by running water?

C

1. A cube with an edge of one centimeter is cut into 1000 cubes of equal size. What is the length of one of the small cubes? How much surface area is exposed by one of the small cubes? What is the total surface area exposed by the 1000 smaller cubes? If this were a cube of earth material, what effect would the increased surface area have on the rate of weathering?
2. Would the weathering of 1.5 meters of limestone and the weathering of 1.5 meters of sandstone produce soils with the same thickness? Explain.
3. Material on the top of a hill was found to be 30 per cent limestone fragments. Limestone bedrock exists 30 meters below the surface. The closest limestone deposit is 160 kilometers away. How could you account for the high content of limestone fragments in the soil materials? Assume that the material at the top of the hill had not weathered from the limestone bedrock.

Suggested Readings

Books

Donahue, Roy L., *Soils: An Introduction to Soils and Plant Growth*. Prentice-Hall, Inc., Englewood Cliffs, N.J., 1965.

Leet, L. Don, and Judson, Sheldon, *Physical Geology*, 4th ed. Prentice-Hall, Inc., Englewood Cliffs, N.J., 1971, Chapter 6.

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U.S. Department of Agriculture, *Soil: Yearbook for 1957*. U.S. Government Printing Office, Washington, D.C., 1957.

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Ellison, Walter D., "Erosion by Raindrop." *Scientific American*, November, 1958.

Judson, Sheldon, "Erosion of the Land—or What's Happening to Our Continents?" *American Scientist*, (Vol. 56), Winter, 1968.

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Foth, Henry, and Jacobs, Hyde S., *Field Guide to Soils*. ESCP Pamphlet Series, Houghton Mifflin, Boston, Massachusetts, 1971.

10. Sediments in the Sea

To learn how sediment is distributed in the ocean and the kinds of deposits that are formed, oceanographers and marine geologists sample the sea floor. Visibility in water is limited to 100 meters at best. Even with the help of deep-diving submarines and remote-controlled underwater television cameras, man has seen only a few hundred square kilometers of the sea floor. The oceanographer must rely on other methods of study.

In the spring of 1971 the newest United States research vessel, Melville, cruised in the Bay of Bengal on its maiden scientific voyage. On the ship's bridge was a satellite navigation receiver. It permitted the ship's officers to determine their position within a few meters. On the stern was a compressor that pumped air under high pressures to a small, streamlined chamber that trailed in the water behind the Melville. About once a second, the pressure in the small chamber was released suddenly, producing a loud bang. The sound waves traveled through the water and through the sediments on the bottom of the Bay of Bengal. They finally bounced off the solid rock beneath the sediments and back up to the ship. The time required for the sound waves to travel from the "air gun" through the sediments and back was computed automatically in a recorder. That information plus the position from the satellite navigator went into a computer in the scientists' laboratory. From the computer came a continuous record of the thickness and type of sediments on the floor of the Bay of Bengal.

For 30 days, the Melville sailed along a zigzag course, from the northernmost part of the Bay to the waters south of the equator. Each day the scientists aboard became more and

more excited. Their data indicated great thicknesses of sediments on the sea floor. When that leg of the cruise was complete, they knew that the Bay of Bengal contained the greatest mass of marine sediments known to man.

Spreading from the huge delta of the Ganges and Brahmaputra rivers, a submarine fan covered 3,000,000 square kilometers and reached thicknesses of 15,000 meters. At least 30 million years had been required to deposit the sediments. Using space age technology, scientists had learned more about this great volume of sediment in 30 days than they had learned in the previous 30 years.

Marine Sediments

10–1
Investigating the deposition of sediments

The violent rush of a stream down a mountain may capture your interest more than the quiet lake into which it empties. Even the sluggish Mississippi River seems more dynamic than the Gulf of Mexico into which it flows. However, major parts of the rock cycle go on day after day, year after year, hidden from view in the dark solitude of the deep ocean. One example is the deposition on the sea floor of weathered materials from the land.

Procedure

Set up the equipment as shown in Figure 10–2. Fill the tube almost to the top with water. Drop a small amount of each sediment into the column and record the time it takes to reach the bottom. Make three trials for each grain size. Then, use the average time of the three trials to make a graph of settling time versus grain size.

1. Is there a place on your graph where the slope of your curve changes markedly? If so, why do you think this happens?
2. State the relationship between settling time and grain size.

Next, drain off enough water so that the col-

Figure 10–1
Sediment carried to the sea by rivers builds the beaches and sand flats along coasts.

umn is only half full. Drop in a handful of mixed sediments and observe what happens. Do this several times.

3. *Describe how these mixed sediments become arranged above the other sediments in the column.*
4. *Where in nature might you find deposits like those formed in this investigation?*

10–2
Sediments reach the sea.

The products of weathering reach the sea in different ways, but most are brought by rivers. As the materials carried by a river reach the coastal lands, they enter a different environment. Where the fresh and salty waters meet—called an **estuary**—the speed of the river decreases. So does its capacity to carry sediments. The coarser sand particles carried by the river settle quickly. Sediments that may have been in the rivers for years and transported for thousands of kilometers are abruptly dumped. Estuaries at the rivers' mouths, are settling basins similar to lakes. Both estuaries and lakes brake the movement of eroded material toward the deep ocean basins.

At the mouths of all rivers, the sediments form triangular-shaped deposits called **deltas.** The Nile Delta of Egypt is shown in Figure 10–3. A delta keeps its shape if there is a balance between the amount of sediment brought by the river and the amount carried away by ocean waves that strike the shore. The Nile Delta had been in perfect balance for thousands of years until 1964 when Egyptians built the Soviet-designed Aswan Dam. The dam disturbed the flow of sediments.

The Delta and its beaches along the Mediterranean shore are now deprived each year of 130 million tons of rich sediments formerly carried by the river. The muds are deposited uselessly behind the Aswan Dam. As a result, the Mediterranean waves are eroding the Delta. Rich soils are no longer dropped on the Nile Valley and Delta by flooding waters. For the first time in recorded history, farmers must use commercial fertilizers to raise their crops.

A similar, though less disastrous, case of erosion was created at the Colorado River Delta in Mexico by the construction of a series of dams in the United States in the 1930's and

FIGURE 10–2

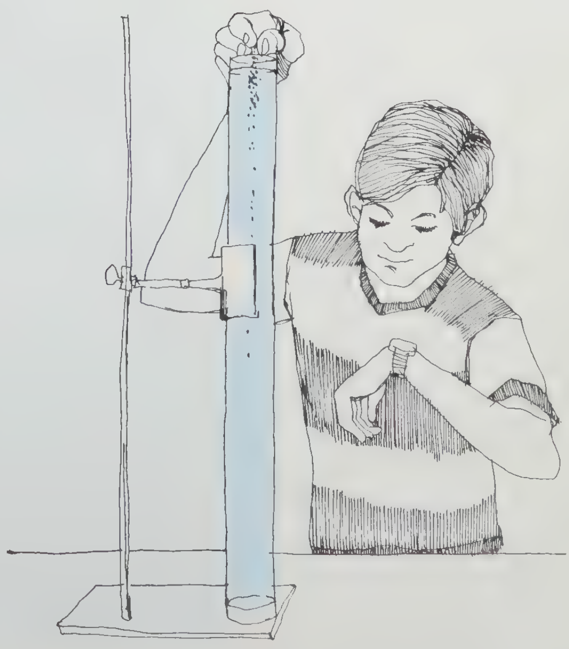
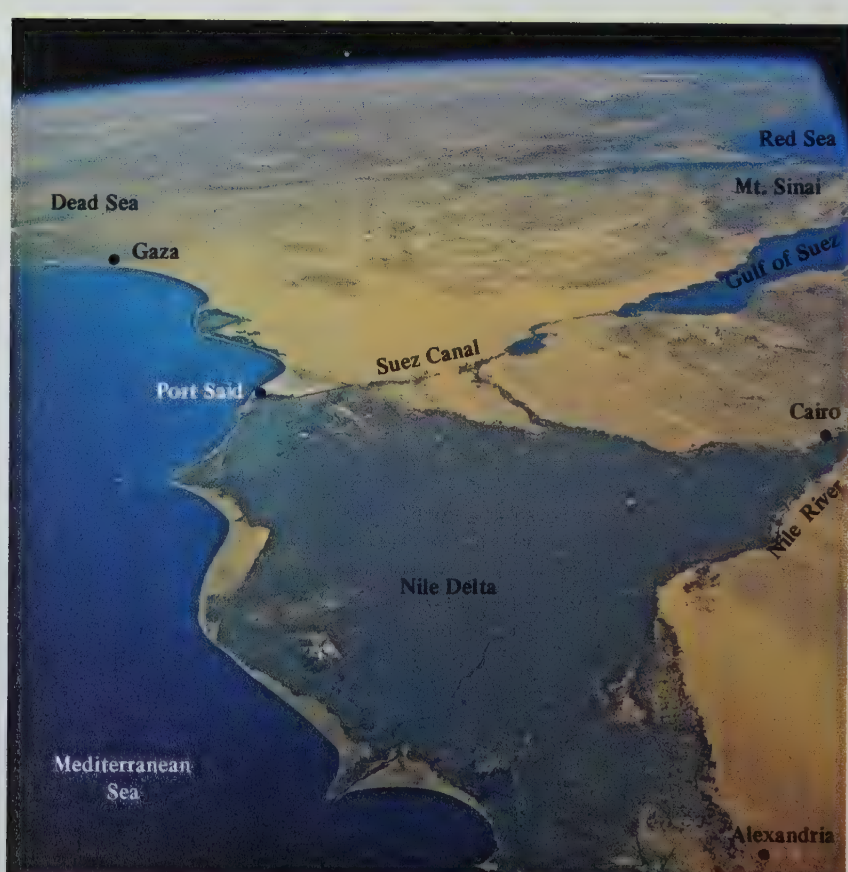


Figure 10–3
Compare the Mississippi Delta (top) with the Nile Delta.



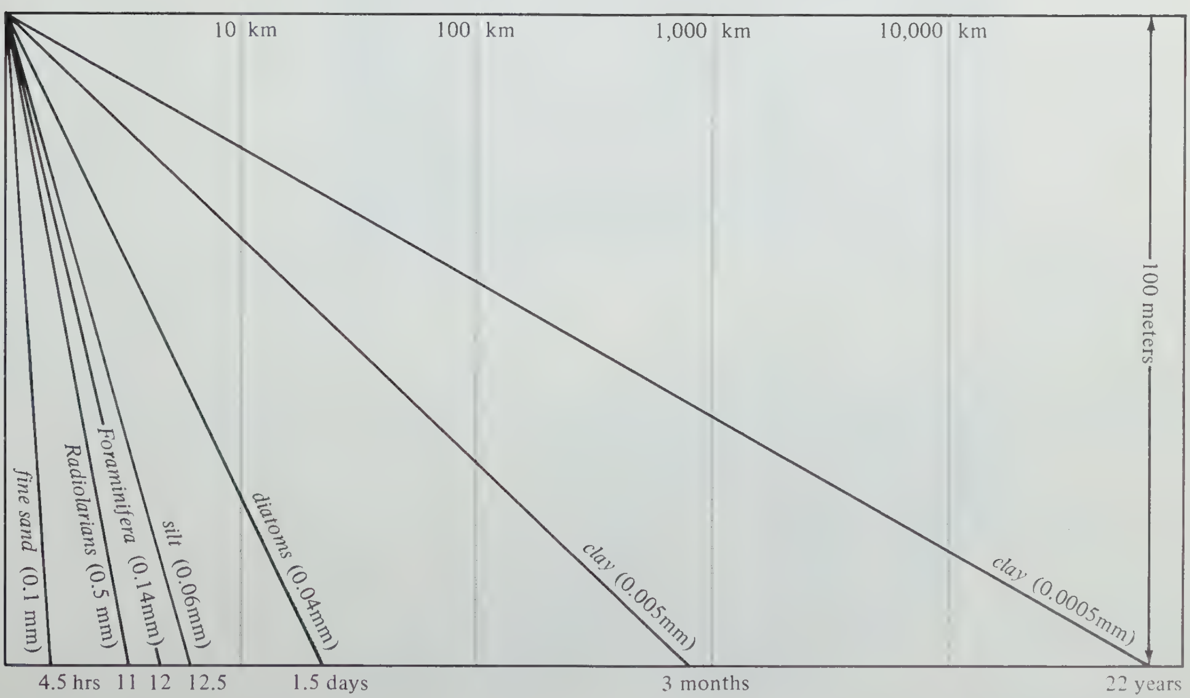
1950's. Sediments are no longer reaching the Colorado Delta, and it is eroding. There is no human population on this delta, so its change is hardly recorded.

Just the opposite is true of the Mississippi Delta. It has grown 15 kilometers into the Gulf of Mexico since the Civil War. Here is one place along the coast of the United States where man can see new land added during his lifetime.

Not all of the material carried to the sea by rivers is deposited near the mouth of the river. Some particles enter the sea without settling to the bottom. (See Figure 10–4.) Other material is moved along the seacoast away from the mouths of rivers by nearshore currents.

The sand, silt, and colloidal particles that reach the ocean settle at different rates, depending mainly on their size, shape, and density. This was evident in Investigation 10–1. At the same time the particles are settling, they are also carried along by ocean currents. They may travel far before reaching the sea floor. It depends on the settling rate of the particle, the speed and turbulence of the current, and the depth of water. Look at the settling rate for the finest particle noted in Figure 10–4. Clearly, such particles would be deposited far from the river that brought them to the sea. Suppose the finest particles were in surface waters where

FIGURE 10–4
In moving water, particles are carried different distances before they settle. In this example the current is flowing at 10 centimeters per second. How does the size of the particle affect the settling rate?



the upward movements of waves were as great as the settling rate of the particles. They might never reach the sea floor.

10–3 Sediments accumulate on the ocean floor.

The products of erosion eventually fall to the ocean floor. Let us look first at the ocean areas near land masses where processes that move sediment are most active. The **continental shelves** are submerged parts of the continents bordering the ocean. (See Figure 10–5.) The depths of the shelves beneath the surface of the sea vary from one coast to another. Even along the east coast of the United States, the depths range from 50 to 150 meters.

Beyond the continental shelf the sea floor dips more steeply. This region is called the **continental slope.** Even though the slope becomes steeper, the incline is only about the same as an aisle in a theater. If Figure 10–5 were drawn to scale, it would show a nearly straight line, not a dramatic plunge. At the base of most continental slopes, there is an apron of sediments that have moved down the slope and come to rest in deep water. This apron is called the **continental rise.**

Shelves, slopes, and rises border all the continents. Although their origins have been debated for many years, it is clear that the shelves and slopes are shaped by both erosion and deposition. Both are important. During parts of the ice ages when sea level was lower, erosion could smooth the surface of the shelves. Now that the shelves are submerged, deposition is more active. In the Gulf of Mexico, for example, the shelf and slope features are the result of deposition. In some places along the east coast of the United States, the two processes acted together to shape the submerged features. The origin of a continental rise never varies, however. No matter where it is studied it is caused by deposition.

Many deep submarine canyons cut across the continental slopes and into the continental shelves. (See Figure 10–7.) In some ways they resemble canyons in mountains on land. Some are enormous, extending hundreds of kilometers from near shore into the deep-sea basins. In southern California, some canyons come so close to shore that fishermen can drop their fishing lines from piers into the 60-meter deep water at the head of a canyon.

The canyons off the coast of southern California have been studied in great detail. They reach depths of about 500 meters, and many appear to be extensions of canyons on land. It was first thought that the canyons were carved by rivers during the ice ages, when sea level was 100 meters lower than it is today. In other parts of the world, however, canyons dive more than 3,000 meters below the surface of the sea. The Hudson Canyon near New York City is one example, and the greatest of all begins in the mouth of the Congo River. It is clear, therefore, that submarine canyons are

Figure 10–5
A cross section of a typical continental margin.

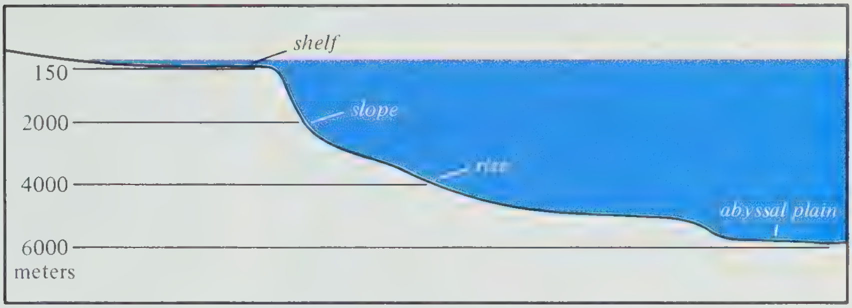
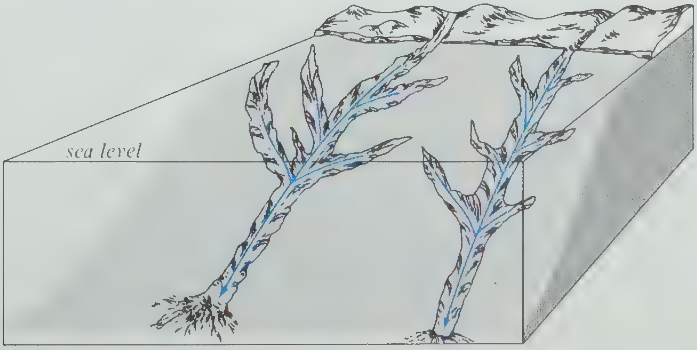


Figure 10–6
A "sandfall" about 10 meters high in a submarine canyon off Baja California.

Figure 10–7
Sediments moving through a submarine canyon are deposited at its mouth.



not the remains of canyons cut by rivers. Submarine erosion must play the major role in forming these canyons.

Although submarine canyons differ in length, depth, and kinds of rocks, they all have one thing in common. On the sea floor at the mouth of each canyon is a large, fanlike deposit of sediments. These deposits are like fans formed on land, but they are generally much larger and cover great areas of the sea floor. The Bengal Fan in the Indian Ocean is the best example currently known. It is not unusual to dredge up shallow-water shells and twigs from the fan. So we know the sediments came down the canyons. The flow of such great masses of sediments can erode the canyons.

Beyond the continental slope, at depths greater than 3,000 meters, lie wide, slightly rolling plains. They cover 63 per cent of the sea floor. That is nearly one-half of the earth's surface. (See Figure 10–8.) These plains are interrupted by many mountains and deep trenches. In the Atlantic Ocean the plains are hundreds of kilometers wide. They begin at the continental slopes and reach to the mid-Atlantic ridge. In the Pacific Ocean basin they begin at the great island chains instead of the continental slopes. In Figure 10–10 (pages 220–21), you can see the deep trenches between the land and the ocean floor in the Pacific. A good example is the Chile Trench along the South American coast. Thus, in the Pacific Ocean the sediments that move across the continental rise are deposited in deep-sea trenches instead of forming broad plains.

Sedimentary deposits at the mouths of submarine canyons blend into the deep-sea plains. The materials of the fans and the plains both come from the land. Masses of stirred up sediment flow down the canyons and slopes and spill out onto the plains. Such flows are called **turbidity currents.**

10–4
Investigating turbidity currents

Coarse fragments are found at the mouths of submarine canyons. They arrived there by streaming across the canyon floor. So far no one has been on the sea floor at the precise moment when a turbidity current has moved down a canyon. Therefore, we don't know exactly how they look. But you can study such currents by using a laboratory model.

Procedure

Set up the equipment shown in Figure 10–9. Mix a slurry of soil and tap water. What do you think will happen when you pour the slurry into the sloping column of water? Test your prediction. Pour 10 or 12 more slurries of the same material into the column. Let every second or third one settle. Compare the rate of movement of later slurries with earlier ones. Remove overflow water ***carefully*** *so you don't disturb the settled sediment.*

1. *Did the results of your investigation agree with your prediction?*

2. *Describe the speed and motion of the material as it travels down through the plastic column.*
3. *How do you suppose turbidity currents similar to the ones you produced are caused in nature?*
4. *How can turbidity currents carry coarse sediments far out into the ocean?*
5. *Coarse continental sediments are found throughout the basins in the Atlantic. Why are they not found in the Pacific basins?*

10–5
Some sediments form in the sea.

If you examined a sample of mud from the sea floor, you would see that all of the material did not come directly from the land. You would notice remains of marine organisms and tiny, sharp mineral crystals that could not have lasted through a long land-to-sea journey. The shells and tiny mineral crystals are formed from ions carried into the sea by rivers.

FIGURE 10–8
The percentages of the earth's surface above and below sea level. What percentage is above sea level?

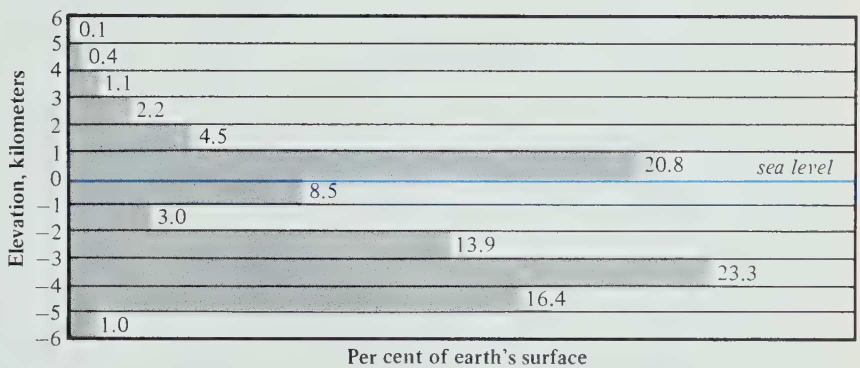


FIGURE 10–9

FIGURE 10–10

MAP OF THE WORLD

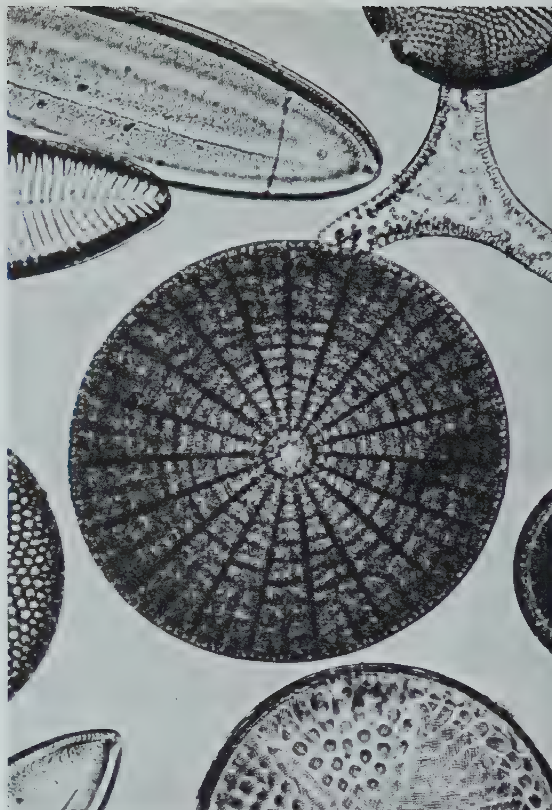
APPROX. SCALE AT EQUATOR

0 2000 MILES

0 2000 KILOMETERS

OCEAN DEPTHS – IN METERS

0 TO 200 (CONTINENTAL SHELF)
200 TO 3000
3000 TO 5000
5000 AND OVER
TRENCHES

Marine plants need certain ions to grow, especially the nitrates, silicates, and phosphates. The most familiar marine plants are seaweeds and grasses that grow near shore. (See Figure 10–11.) However, these do not compare in number or total volume with the vast quantities of microscopic plants that live in the open ocean. There may be tens of thousands in a single liter of water! The animals are also numerous. Larger organisms, such as young fish, feed on the tiny ones as part of the "food chain."

The number of animals and plants in the surface water is partly controlled by the amounts of nutrient ions and the rate of feeding. The plants can rapidly use up the nutrient ions in a still body of water such as a lake. Plant and animal life is most abundant, therefore, near mouths of rivers or in ocean areas where phosphate and nitrate nutrients are constantly brought up from the depths of the sea to the surface.

FIGURE 10–11
(top left) Seaweed-covered rocks along the Massachusetts coast.

FIGURE 10–12
(top right) The delicate shells of microscopic marine plants called diatoms.

FIGURE 10–13
(bottom left) Remains of foraminifera are found in deep-sea sediments.

FIGURE 10–14
(bottom right) Phillipsite crystals from the Challenger Reports.

Waters rise to the surface along the northern border of the great current flowing around Antarctica. (See Figure 4–16.) Here the nutrient-rich, rising waters support an enormous population of microscopic plants with silica shells called **diatoms** (Figure 10–12). The sediments on the nearby sea floor are composed almost entirely of diatom shells.

The most common organic remains in marine sediments are the carbonate skeletons of microscopic animals called **foraminifera** (Figure 10–13). Thousands of species of foraminifera live in all of the surface waters of the sea, feeding on plants such as diatoms. Most marine sediments contain remains of these species.

10–6
Minerals form in the sea.

When sediments were analyzed from the *Challenger* Expedition, the mineral **phillipsite,** was found to be abundant in the deep-sea deposits of the Pacific Ocean (Figure 10–14). Phillipsite, an aluminum silicate rich in potassium and sodium, is of interest because it is not found in rocks on the continent. The crystals have been collected only from deep-sea sediments. Furthermore, phillipsite occurs as isolated crystals in sediment, rarely touching one another. It seemed clear to the *Challenger* scientists that the mineral had crystallized on the surface of deep-sea muds. This was the first real evidence that the deep-sea environment differed greatly from the shallow seas near continents. Minerals formed in the deeps that could form nowhere else on earth.

HMS CHALLENGER

When HMS *Challenger* put to sea in the winter of 1872, it became the first ship commissioned just for the purpose of studying the ocean. The British Admiralty and the Royal Society, seeing the need to learn more about the mysterious ocean floor, sent *Challenger* on a three and one-half year cruise. The results of that magnificent voyage filled 50 volumes and were published as the *Challenger Reports.*

This sailing ship carried the men who started oceanography as a science. The leader was Sir C. Wyville Thomson, a professor of natural history, who had spent several summers on British naval ships collecting marine organisms. He later described these discoveries of the new underwater world in his great book *The Depths of the Sea.* When Thomson's health failed toward the end of the voyage, Sir John Murray headed up the expedition. Murray was a famous Canadian biologist and oceanographer. He saw to the careful completion of all observations and collections, and when the voyage was finished in 1876, he edited the *Challenger Reports.*

The *Challenger* scientists observed animal and plant life, dredged the deep-sea floor, took samples of water from all depths, and measured temperatures all through the oceans. They used thick rope up to eight kilometers long to make depth measurements at thousands of points in the Pacific. They learned among other things that the sea floor was as varied as the land with massive mountain ranges, deep valleys, and plains.

Soon it was learned that many deposits on the sea floor have formed by precipitation from sea water. Widespread deposits of manganese lumps, such as those in Figure 10–15, formed in this way. These, too, were first discovered during the *Challenger* Expedition. Exploration during the International Geophysical Year (1957–58) disclosed thousands of square kilometers, especially in the South Pacific Ocean, covered with manganese deposits.

The manganese, with small amounts of cobalt and iron, occurs as grains, nodules, slabs, and coatings on rocks. (See Figure 10–16.) Most of the nodules are about five centimeters in diameter. It is not known how fast they form. They must grow faster than the rate of

deposition of particles and organic debris. Otherwise, the first tiny grains of manganese formed would be covered with sediment and not grow any larger. Consequently, manganese nodules form only in areas where there is little deposition of sediment.

Phillipsite and manganese nodules are deep-sea minerals. Under some conditions, different minerals can form in shallow water. Calcium carbonate is the most common. It is soluble in sea water. The amount dissolved depends on the amount of carbon dioxide in the water. Sea water is normally saturated with calcium carbonate.

ACTION *Keep adding salt to a small glass of water until no more will dissolve. Filter the water and allow the clear filtrate to stand undisturbed for one week while crystals form. Blot the crystals dry with filter paper. If possible, use a magnifying glass to study their shape.*

FIGURE 10–15
(top) Manganese nodules about five centimeters in diameter. They were found on the ocean floor at a depth of four kilometers. The animal is a sea cucumber.

FIGURE 10–16
Drawings of manganese nodules from the Challenger Reports. *The cross section (top left) shows concentric rings.*

When cold water from deep in the sea rises over a shallow bank, the water warms. This drives off some of the dissolved carbon dioxide in the water. (Warm water can't hold as much carbon dioxide as cold water.) On such shallow banks there is usually a thick growth of sea plants. They carry on photosynthesis, which further reduces the amount of carbon dioxide in the shallow water. As a result, calcium carbonate precipitates onto the banks, as in Figure 10–17.

Thought and Discussion

1. Do all particles eroded from land stop at the edge of the sea?
2. Where do the sediments at the mouths of submarine canyons come from?
3. Where do the materials come from that organisms use to make their shells?
4. How do manganese nodules develop?

FIGURE 10–17
Carbonate deposits form in the warm, shallow tropical waters off the Bahamas.

The Continental Margins

10–7
The shorelines have moved.

The ground beneath you was once a beach. Waves washed up and down the sand carrying shells, seaweed, and pebbles. It is even possible that children once played on this beach, which has long since disappeared.

Evidence of ancient beaches comes mainly from marine sedimentary rocks. Today these rocks cover about three-fourths of the continents. Most of the rocks contain fossils indicating that they were formed in shallow seas. Certain places on the continents have no sedimentary rocks. In these places erosion has stripped them away. Evidently, the continents were at various times at the bottom of shallow seas like those now covering the continental shelves. As the ancient seas advanced or retreated across the land, beaches formed at their edges.

At times sea level was lower than it is today. During the ice ages, vast quantities of water evaporated from the sea and dropped upon the land as snow, forming glaciers. The glaciers

covered much of the land in the Northern Hemisphere. Water removed from the sea to make up the glaciers lowered the level of the ocean. Teeth from prehistoric elephants have been recovered from the continental shelf off the east coast of the United States. They were in 60 meters of water along with shells of animals that live only in shallow water or mud flats.

As glaciers advanced or retreated, they alternately held and released great volumes of water. The level of the sea rose and fell by as much as 150 meters. Beaches, sand dunes, and mud flats that must have been formed then, have been changed or removed by erosion and deposition. The result is the rather level shelf surface of today.

From Investigations 10–1 and 10–4, you know that coarse sedimentary material is deposited rapidly. Finer fragments are usually carried far out to sea. (See Figure 10–18.) This pattern of sediments is obvious on the continental shelf and slope off the eastern United States. In some cases, however, layers of sand and mud form one on top of the other. As a delta grows out into the sea, a layer of coarse sand is formed on the beach. The sand gradually pushes out onto a bed of fine clay that had formed earlier on the outer edge of the delta. In contrast, a retreating shoreline would de-

FIGURE 10–18
Most sediment brought to the sea comes through the great river systems of the world. Some sediment is deposited in lakes. This plume of sediment is at the mouth of the Flathead River in Montana.

posit mud on sand. As the shoreline advances and retreats, layers of sand and mud alternate.

Beaches are easily eroded because the sediments are loose. If sea level falls, stream erosion wears away the beach deposits. The fragments are scattered into the lowered sea and along the new shore. If sea level rises, waves breaking over the old beach soon destroy it. Ancient beaches are rarely preserved within the layers that make up the shelf. However, remnants from old beaches such as pebbles, shells, and sand are there, having been scattered over the new shelf.

Imagine the entire seashore with its breaking waves, sand dunes, and beach umbrellas moving slowly back and forth across the continental shelf. The actual migration of the seashore would take place so slowly that you could not notice the change from day to day or even from year to year. Even so, by the standards of geologic time it has been rapid.

10–8 The thickening continental margins

For millions of years a river system carried sediments into an ocean basin. This basin, now filled, is the Mississippi Valley. The delta is still growing seaward, as deltas have in this region for millions of years. In fact, the first deposits were laid down near Cairo, Illinois.

Each day the Mississippi carries two million tons of sediment to the Gulf of Mexico. This sediment is eroded from 41 per cent of the land area of the United States. Some of the particles are deposited on the delta and in the shallow water along its edges. Some are swept along the coast into bays and marshes. Others travel down the slope of the delta onto the submerged fan in the Gulf of Mexico.

For tens of millions of years, the river has been carrying soils and sediments to the sea. As you would expect, the Gulf of Mexico is gradually filling up. (Most of the sediments come from the Mississippi, but other rivers also enter the Gulf.) Five other coastal regions of the world receive similar volumes of sediment: West Africa off the Congo River, South America off the Amazon and Orinoco, China off the Yangtze, India off the Ganges, and Siberia off the Lena River. In each case, the filling has been going on for millions of years, and a broad, flat coastal plain has been formed. (See Figure 10–19.)

Geologists exploring for oil have learned that the sedimentary layers in the lower Mississippi Valley and along the coast are 15,000 meters thick and bend down into the earth's crust. These layers along the north coast of the Gulf of Mexico have all been deposited by the Mississippi River. Far out in the Gulf, sediments are only a few hundred meters thick.

Deep wells drilled along the east coast of the United States have shown that the sediments there are nearly as thick as those along the Gulf Coast. The deposits have come from the several rivers draining the Appalachian Mountains. In contrast to these thick deposits near shore, detailed studies made in many of the ocean basins of the world have shown that sediments in the deep sea are only from 300 to 500

meters thick. Compare those with the thickness of sedimentary layers along the Gulf of Mexico and the east coast. It is easy to conclude that thick sedimentary layers are unique to continental margins.

All of the sediments in the layers that make up the continental shelves have shallow-water features. One infers that each layer was deposited in shallow water. To account for the great thickness of the sediments one must conclude that the shelves are sinking. We have a dynamic picture, then, of a gradually sinking continental margin on top of which sediments are continually added by great rivers (Figure 10–20).

At the same time, masses of material spread farther and farther from the original shore. The shelf and slope are pushed out into the ocean

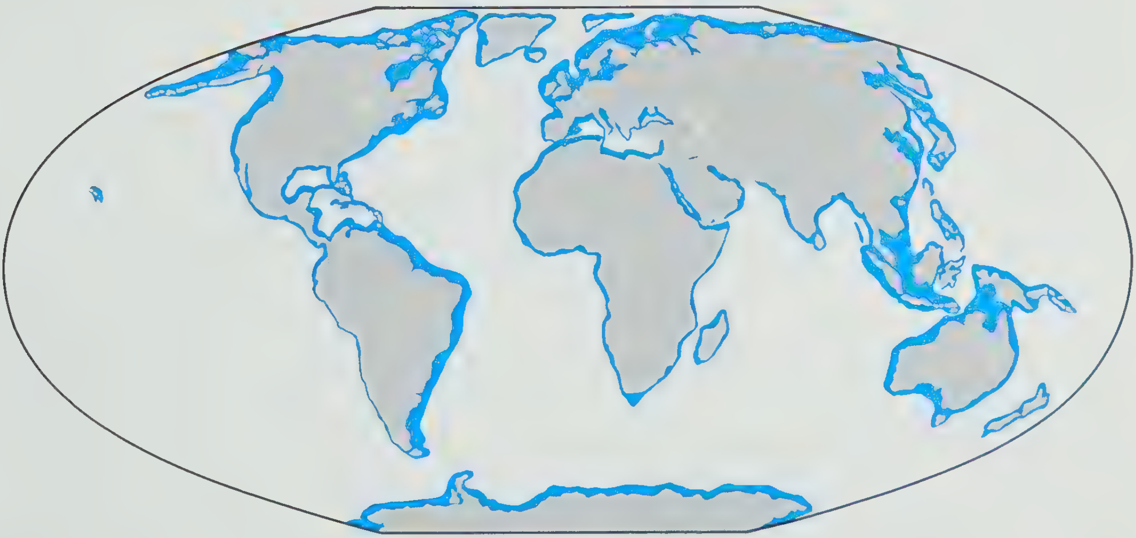


Figure 10–19
The colored areas bordering continents mark the continental shelves.

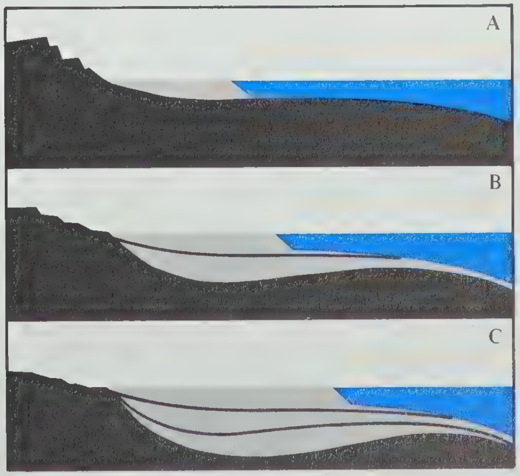


Figure 10–20
A sequence of events in the history of a continental shelf as a delta grows seaward. How do the middle and bottom frames differ?

basin. And a great deal of material slides down the continental slope and through the submarine canyons to form the thick layers of the continental rise. If the rate of deposition keeps pace with the rate of sinking, or **subsidence,** there is no change in water depth or in the position of the shoreline. What happens when deposition is faster or slower than subsidence?

Careful measurements over the last century have shown that the high tide mark has changed at some shorelines but not at others. These changes could not be caused by glaciation. The growth and retreat of glaciers would cause all shores to be alternately covered and then exposed. Subsidence is active today where great thicknesses of sediments are still forming (along the east and Gulf coasts of America). Where such continental margins are absent (off the west coast of America), there is no evidence of subsidence.

Thought and Discussion

1. How would you prove that the shorelines of the ocean are not stationary?
2. What do great thicknesses of sediment such as those found along the Gulf of Mexico indicate?
3. How do near-shore basins of deposition develop?
4. How do glaciers influence changes in sea level?
5. How do the deposits of continental shelf off the east coast of America compare with those in the Gulf of Mexico?

Unsolved Problems

The greatest unsolved problem of the ocean basins is their origin. To learn how they formed requires detailed studies of the rock structures throughout all ocean basins. This task is far from completed.

The thinness of sediments in the deep-sea basins probably relates to their origin. Thick deposits near the shore are understandable. But according to the measured rates of deposition in the deep sea, there should be at least 3000 meters of sediments. Instead, there are only 300.

Chapter Review

Summary

The oceans of the world are immense. They cover 71 per cent of the earth's surface and are very deep. If all of the land masses were scraped into the oceans, the entire earth would still be covered with 200 meters of water. In fact, the lands *are* being scraped into the oceans by erosion. The United States is being eroded at a rate of about five centimeters every thousand years. Rocks and soils are worn away and ultimately deposited in the ocean basins. About 12 cubic kilometers of sediment is deposited in the oceans each year.

Sediments are moved and deposited by the processes you investigated in this chapter. These sediments are not only deposited in deltas and continental margins, but they are spread over

great areas of the sea floor and out into the deep-sea plains.

The shelf, slope, and rise of the continental margins of most of the major land areas of the world are depositional features. They make up tremendously thick deposits along the borders of the continents and ocean basins. The Atlantic and Gulf Coast of the United States are depositional areas that are slowly sinking to compensate for the great load of sediments.

Questions and Problems

A

1. What happens to the settling speed of a particle of volcanic ash as it descends through the air and crosses the air-sea interface?
2. Some submarine landscape features such as volcanoes and canyons show sharper outlines than their counterparts on land. How would you explain this?
3. What determines the rate of production of microorganisms in the ocean and the quantities in which they are deposited on the sea floor?

B

1. How do turbidity currents move and distribute sediment on the sea floor?
2. What are some sediments that originate in the sea and how do they form?
3. How do you know that glaciers are not the only cause of changes in sea level?

C

1. The average thickness of sedimentary rocks in the earth's crust is about 0.74 kilometer. Assume an average rate of deposition of 40 millimeters per 50,000 years. Assume that this rate has been uniform for millions of years. How long did it take to accumulate the sedimentary rocks of the crust? Does your answer equal the total time elapsed since the deposition of the first sedimentary rocks? Why or why not?
2. It is believed that some submarine canyons may have been carved by rivers that flowed across the continent. How could this happen? What evidence is there that all these canyons were not produced in this way?

Suggested Readings

Bascom, W., *A Hole in the Bottom of the Sea: Story of the Mohole Project.* Doubleday & Company, Inc., New York, 1961.

Behrman, Daniel, *The New World of the Oceans.* Little, Brown & Co., Boston, 1969.

Emery, K. O., *A Coastal Pond.* American Elsevier Publishing Company, Inc., New York, 1969.

Ericson, D. B., and Wollin, G., *The Ever-changing Sea.* A. A. Knopf, New York, 1967.

Shepard, F. P., *The Earth Beneath the Sea,* rev. ed. John Hopkins Press, Baltimore, 1967.

11. Mountains From the Sea

Early in this century an extraordinary fossil discovery was made high in the Canadian Rockies. A geologist's pack horse stepped on a loose slab of black shale and turned it over. There, embedded in the dark rock, were the remains of animals that had once lived in the sea! The soft parts of delicate marine organisms, such as jelly fish and marine worms, had been beautifully preserved. This fossil discovery showed that the rocks making up that part of the Rocky Mountains came from the sea.

More than five hundred million years ago the fossils in the rocks were living animals in a shallow, warm sea. The animals sank into the mud after their death. As more and more sediment was deposited, the animal remains were compressed by deposits several kilometers thick and formed fossils.

In the previous chapter you saw what happened to sediments when they finally reached the sea. Now you will explore some of the features of the sea floor and some of the crustal activity at the margins of continents and in the depths of the sea. Then you can begin to form some idea of how sediments from deep in the ocean can become part of the highest mountains on the surface of the earth.

Geosynclines

11–1 Investigating inland marine sediments

About 1837 James Hall, a geologist on the staff of the New York State Geological Survey, was puzzled by the great layers of sedimentary rocks in western New York. He was intrigued by variations in the thickness of layers and puzzled by the evidence that each layer had been deposited in shallow water. Also some layers were tilted, but must have been deposited horizontally.

PROCEDURE

Using the same kind of information available to James Hall, we will retrace some of his field studies. The data comes from the area between Buffalo, New York and western Massachusetts (Figure 11–1). Study the photographs in Figure 11–2 and see if you can reconstruct past events from the evidence presented.

Draw a cross section along the route shown in Figure 11–1. At each station make sure the rock layers are the proper thickness, as listed in Figure 11–3. (Rock Unit I is on top of Rock

FIGURE 11–2
1. *Niagara River flowing over sedimentary layers at this station.*
2. *Flat-lying sedimentary rock.*
3. *Rock layers.*
4. and 5. *Rocks containing fossil coral.*
6. *Fossils and thin layering are common.*
7. *Erosion has exposed slightly warped sedimentary layers.*
8. *Rocks are contorted and shattered.*
9. and 10. *Evidence of igneous activity.*

FIGURE 11–1
Stations in this investigation.

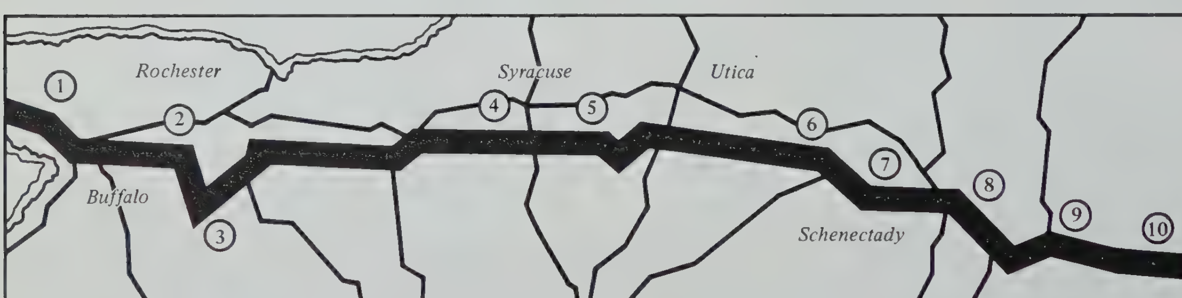
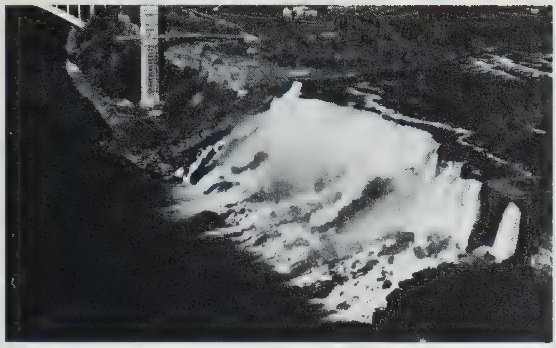


FIGURE 11–3
Thickness in Meters of Sedimentary Rocks Below Surface Along Route Shown in Figure 11–1

STATIONS	1	2	3	4	5	6	7	8	9	10
ROCK UNIT I	900	1500	1500	1500	1500	2000	2500	0	0	?
ROCK UNIT II	300	350	650	3000	3300	3300	3000	3300	3000	?

1.



2.

3.

4.,
5.

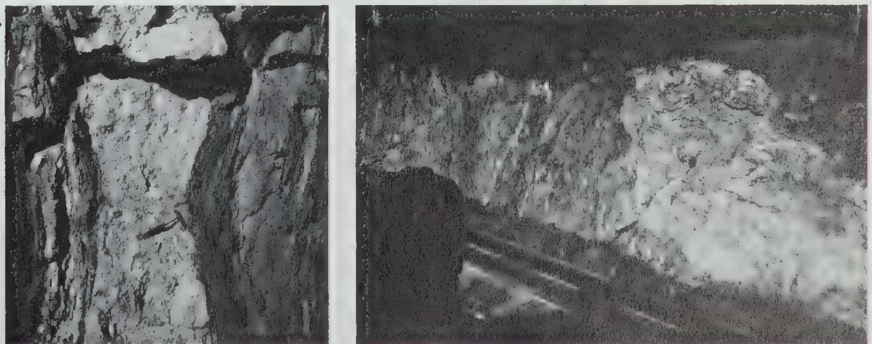
6.

7.

8.

9.

10.



Unit II.) Remember that sediments are deposited in horizontal layers beneath the ocean's surface. Thus, those at the top of a basin must be flat.

1. *What evidence is there from the photographs that these rocks are marine sediments?*
2. *Describe the general shape of the basin shown by the cross section.*
3. *How can you explain the rock types at the last stations as compared with those that were found at the first stations?*

11–2
The layers of geosynclines

James Hall's field trips led him to form the concept of a geosyncline (gee-oh-SIN-kline). He reasoned that great thicknesses of marine sediments containing only shallow-water fossils could only be formed in a wide basin at the continental margin. The basin must have sunk slowly as it was being filled. (Hall did not call this sinking basin of deposition a geosyncline. The name was applied later.)

Hall noted that the sediments became finer grained toward the midpoint between Buffalo and Massachusetts. On either end there were coarse sands and, in some places, pebbles and cobbles that formed conglomerates. He considered these coarse sediments as evidence of nearby land masses. He reasoned there must have been one on the west (the North American mainland) and one on the east ("Appalachia"). A great amount of scientific effort has been expended since Hall's time trying to locate geologic features that might be the remains of such a large land mass. But further evidence of this vanished land called "Appalachia" has never turned up.

Think back to Chapter 10. What is the natural process that could deposit coarse sediments of shallow-water materials on the outer edge of a great continental margin? Can you suggest a reason why James Hall did not consider this possibility?

Suppose that you extended Investigation 11–1 to Pennsylvania and Ohio. You would learn that the rocks there are only one-tenth as thick as the 14,000 meters of layers in New York, although all the rocks were deposited during the same period of time. In many mountainous parts of the world, sedimentary rocks are 10,000 to 15,000 meters thick. But rocks in the adjoining plains representing the same geologic time span are only a fraction as thick.

It is evident in nearly all these cases that the sediments had been deposited in shallow water. The rocks usually contain fossils of organisms similar to those that now live in seas less than 300 meters deep. They also contain remains of ripple marks, the small ridges that are formed by wave action on sediment in shallow water (Figure 11–4).

Such great thicknesses of sediment could have originated in shallow water in two ways. Either deposition took place while the sea floor was sinking or while sea level was slowly rising. Sea level cannot rise in one basin, however, without rising everywhere—to 14,000 meters in this case. There is no evidence of a rise in sea level of this amount, or anything close to it. Even the great variations in sea level during the ice ages was only one one-hundredth as much. Hence, the sinking of the sea floor is a better explanation for the great thicknesses of shallow water deposits.

The idea of a geosyncline where sediments accumulated over millions of years has been a useful geologic tool. With some modifications, Hall's explanations have been used to identify and interpret ancient and modern geosynclines all over the earth. You can see in Figure 11–5 the areas of the earth's crust where there are thick accumulations of shallow-water, marine sedimentary rocks. Clearly, these are the mountain ranges of our landscape and the sites of former geosynclines.

The questions now to be considered are:

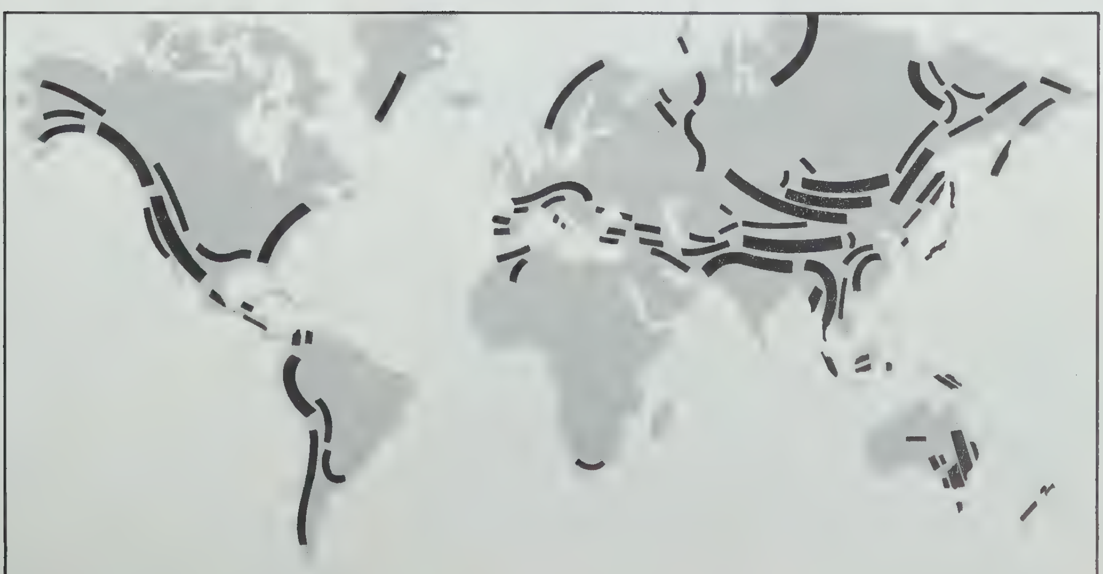
1. How do sediments form in a sinking basin near the continent?
2. How do the basins rise to form long mountain ranges?

a.

b.

FIGURE 11–4
a. *These ripple marks formed on the bottom of an ancient sea.*
b. *Waves form ripple marks on a beach today. Where else might you find ripple marks?*

FIGURE 11–5
Continental regions where some geosynclinal mountains have developed in the past.



11–3 Modern geosynclines

Great thicknesses of sediment have been deposited on the continental shelves, slopes, and rises of the Gulf of Mexico and the east coast of North America (Figure 11–6). The sediments of both coasts are similar to the sedimentary rocks in the inland portion of James Hall's geosyncline in New York. Let us see then how these modern sediments have formed and how they relate to the rocks of the Appalachian geosyncline.

Marine sediments with the features we are interested in are confined to depths no greater than 20 meters: the depth at which waves first begin to "feel bottom." The major volume of coarse sediments is retained shoreward of this depth. Any fine material in suspension is swept across the shelf and out onto the continental slope and rise (See Figure 11–7.) Along the east coast of the United States there is not much sediment on the continental slope. This is because turbidity currents and mud slides carry the material onto the deep continental rise.

The apron of sediments laid down on the continental rise by turbidity currents gradually builds up to enormous proportions. As the rise grows, it backs farther and farther up the continental slope. In response to this growing load, the earth's crust begins to subside (sink) along the outer edge of the continental slope. The depth of water over the sea floor is constantly changing, but the sediments always have features that come from shallow water.

The sediments that are forming the continental rise have a lower density than the rocks from which they are weathered. They are less dense than the underlying rock of the earth's crust and mantle (2.3 g/cm^3 for sedimentary rocks of the upper crust compared with 3.7 for the upper mantle, or about two-thirds the density). Consequently, as a rough rule-of-thumb, for every three meters of sediment added to the rise, the underlying crust will sink two meters.

Looking at the sequence of deposition, we see that there are thin sediments a few meters thick at the coast (Figure 11–8). These grade into thousands of meters of deposits at the rise. The continental margin subsides, mostly under the rise deposits. Thus, the entire area tilts down toward the sea. The tilt is greatest under the continental rise. But, there is even a slight subsidence along the shore (a few millimeters per year). This makes the beach slowly migrate inland.

ACTION *What does a geosyncline look like drawn to scale? Assume an area 500 kilometers across with 20,000 meters of sediments at its thickest. This would be a big geosyncline. Keep this scale drawing in mind when you are considering the movements of the earth's crust during geosynclinal development.*

The wedge of shallow-water sediments grows from the erosion of the nearby land mass. If erosion is rapid, the coastal waters are loaded with suspended mud that is carried across the

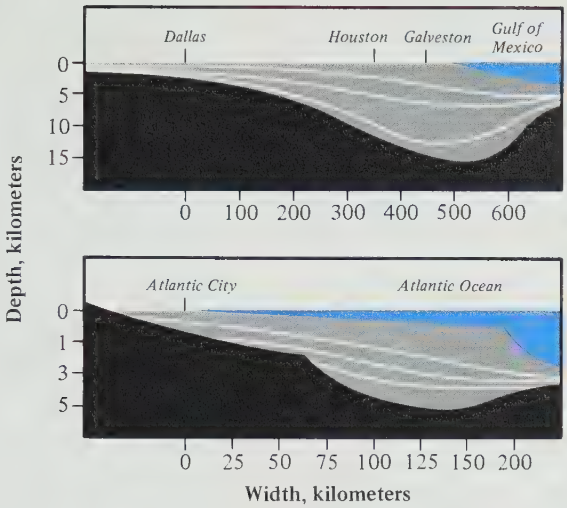


FIGURE 11–6
Cross sections through the Gulf and East Coasts of North America.

FIGURE 11–7
Rip currents carrying sediments through the surf and out into shelf waters.

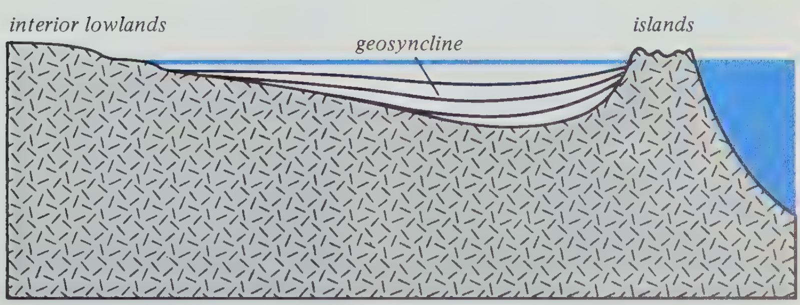


FIGURE 11–8
A cross section of a typical geosyncline.

shelf to the continental rise. This makes the rise grow rapidly and causes more downward tilting of the shelf. As a result the shoreline migrate farther inland. Then a broad and low coastal plain is formed. As you know, that is an area of reduced erosion. So, ironically, early rapid erosion leads in time to less deposition and less subsidence.

11–4 Deformation within geosynclines

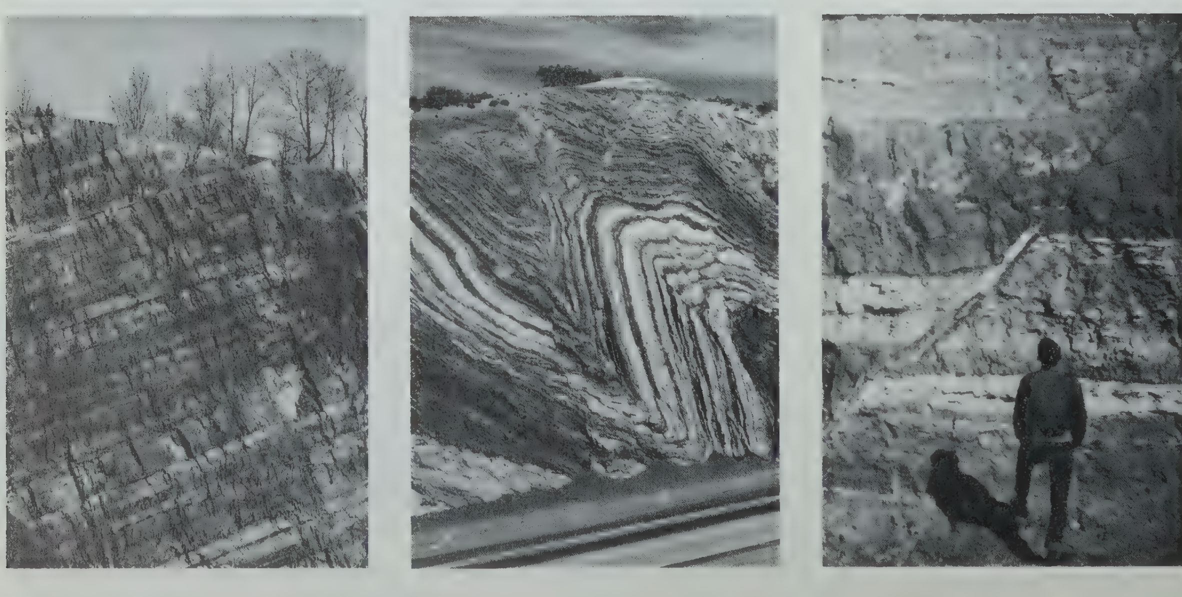
The sedimentary rocks in the center of a geosyncline are thicker than those near the borders. They also differ in other ways. In the field trip from Buffalo to western Massachusetts, the central rocks were bent, broken, and squeezed much more than those at the outer edge. These features are much more obvious than the thickening of the rocks. It is to Hall's credit that he was able to determine the overall shape of the geosyncline.

Rocks that are bent, broken, squeezed, or stretched are called **deformed.** To identify the kind of deformation that has taken place, you must have a good idea of what the rocks looked like before. An inflated basketball someone is sitting on can be described as slightly flattened because you know what the basketball looked like when no one was sitting on it. You would not say that a football was a deformed basketball. In each case you use your knowledge of the object before it was deformed to detect and describe its changes.

Three outcrops of deformed sedimentary rocks are illustrated in Figure 11–9. The folds, faults, and fractures were caused by pressures that squeezed the great layers of sedimentary rocks. Large belts of similarly bent and folded rocks occur in most mountain ranges. In some

FIGURE 11–9
a. *Tilted sedimentary layers*
b. *Folded sedimentary layers near Palmdale, California.*
c. *A fault in sedimentary rocks.*

a. b. c.



instances great blocks of the earth's crust have actually slid on top of other blocks (faulting). All this evidence means that at some stage in the history of a geosyncline, when the sediments have reached thicknesses of 10,000 meters or more, the basin stops sinking and tilting. Great forces begin to squeeze and push the massive deposits. Rocks are deformed from their original horizontal position.

The same question must have occurred to Hall and to every other geologist who studied mountain formations until recent years: what is the source of the squeezing forces that deformed the flat, smooth, geosynclinal sediments? One exciting new theory is described at the end of this chapter.

We cannot see the folding, bending, and squeezing of solid rock. It requires hundreds of thousands of years to deform sediments into contorted layers. It is actually difficult to imagine a solid being folded or bent without smashing to bits.

Materials that tend to resist twisting are said to be *rigid*. Solids are rigid, liquids are not. The resistance to flow in liquids is called **viscosity.** Butter is more viscous than the cream from which it is made.

Solids may act like liquids for very short periods of time. For example, when wet sands are exposed to strong vibrations (from an earthquake or a dynamite blast), the deposit acts like a liquid for several seconds. If the sand is on a slope, there may be a landslide.

Action *If you take an ice cube and strike it with a hammer, it will shatter. Yet, a penny or a quarter laid on the ice cube will slowly sink through it as the ice re-freezes behind the cube. Is ice solid or liquid?*

Rock salt is solid too. You can easily smash it with a hammer. But when salt crystals are exposed to moist air, they will clump and flow together. (This won't happen with iodized salt.) Is salt a liquid or a solid?

All solid materials will flow, bend, and squeeze if forces are applied over a long period of time. Though the rate of deformation may be slow (a few millimeters per thousands of years), the final product of the squeezing of geosynclinal deposits is a long mountain range with rocks greatly changed from their old sedimentary appearance.

Thinking of the sudden landslide, it may not seem so strange that rocks can bend and flow. Actually, many substances we consider solids may flow or change under normal forces such as gravity. For example, try to decide which of the following are solid or liquid:

limestone	tar
pure water at −50°C	rock candy
pure water at 50°C	modeling clay
gelatin	steel spring
glass	silly putty
fresh paint	caramel candy
rubber	

Thought and Discussion

1. What evidence did James Hall have for his idea of a shallow depositional basin?
2. Why are the sediments in geosynclines so thick?

3. Why do continental margins tilt toward the ocean basins?
4. What happens to rock layers when they are squeezed?

Patterns of Crustal Movement

11–5
Investigating earthquakes

To understand how mountains arise from the sea, we need to know more about the earth's crust and how it moves. Earthquakes are a good place to start.

The earthquake of August 17, 1959 at Hebgen Lake, Montana caused the water in the lake to overflow the dam and surge down the narrow canyon of the Madison River. The river, in turn, was dammed by an earthquake-triggered landslide that moved 80 million tons of rocks. Three large faults appeared at the earth's surface, accompanied by land movements that permanently tipped the floor of the lake (Figure 11–10). The earth tremors also changed the eruption times of Yellowstone Park's geysers.

Not all earthquake activity is so spectacular. There is constant shaking going on that is so slight that only seismographs can detect it.

Since beginning your Earthquake Watch, you have been locating the epicenters of large and small earthquakes and the depths of earthquake focuses. You now have some of the data used by scientists to outline the great belts of activity in the earth's crust. Your observations will also help in our discussion of forces beneath the surface.

Procedure

Examine the map of the earth on which you have been recording the epicenters and depths of earthquakes.

1. *What is the general pattern of earthquake distribution? Does it resemble or coincide with any other major patterns of the crust?*
2. *If so, can you relate these features to earthquakes?*
3. *Where did the greatest number of earthquakes take place?*

You have information on the depth of earthquakes within the earth's crust. Choose an area from the active belt around the edge of the Pacific Ocean where deep, intermediate, and shallow earthquakes have occurred. Place a sheet of transparent plastic over the area you select. Next, draw a line at right angles to the coast. Mark the coastline and the location of several shallow, intermediate, and deep-focus earthquakes near the line (Figure 11–11). Now, construct a cross section along the line you have drawn. Using a millimeter rule and graph paper, plot the depth of the earthquake focuses.

From your completed drawing, describe the pattern of earthquake focuses in this area.

4. *How do you interpret the pattern?*
5. *Using Figures 11–5 and 11–13, describe the distribution of earthquakes with respect to (a) volcanoes and (b) mountains that have been uplifted from geosynclines.*

11–6
Island arcs and volcanoes

There are volcanoes, faults, and earthquakes on the ocean floor as well as on land. As you

learned in Investigation 11–5, they seem to be related. Curved chains of volcanic islands form great arcs around the margin of the Pacific Basin (Figure 11–13). The Antilles and East Indies also form a series of island arcs. Many of the volcanoes in these chains are still active and occasionally spew out masses of lava, gases, and vast clouds of ash.

The continental volcanoes seem to be aligned, just like the chains of volcanic islands. El Paricutín, the newest volcano on the North American continent, rose from a farmer's corn field in Mexico in February, 1943. Within the first week, the cone had grown to 140 meters; within the year, 325 meters. In 1952, El Paricutín ceased erupting and is now one of the hundreds of dormant volcanoes along the west coast of North and Central America.

One Sunday afternoon in August 1883, the island of Krakatoa in the Sundra Strait between Java and Sumatra began to rock with a few earthquakes. The next morning, a violent eruption ripped the cone from the volcano and blasted more than a cubic mile of rock into the air. Dust, gas, and ash rose more than 20 kilometers into the atmosphere. The finest pieces of the dust were carried around and around the earth for the next two years before they finally settled. The island of Krakatoa was blown to bits by the eruption. Though there were few people living there, uncounted thousands were killed on nearby islands from the

FIGURE 11–10
A ground break in the Hebgen Lake area of Yellowstone National Park caused by the '59 earthquake.

FIGURE 11–11

seismic sea wave (tsunami) created by the eruption.

Nineteen years later, on the opposite side of the earth, on the island of Martinique, Mt. Pelée began to spew out a gas and boiling water during the early springtime. This minor activity went on for several weeks. The inhabitants of the city of St. Pierre took little notice for they knew the volcano had been active in the past. In late April some ash began to explode from the main vent, but city officials assured the citizens there was no danger. The activity quieted and everyone breathed sighs of relief. But about 8:00 A.M. on the morning of May 8 without warning the volcano exploded in four great blasts. A huge, sulfurous cloud roared down the mountainside and engulfed the city (Figure 11–12). The incandescent gases and dust

FIGURE 11–12
A painting by Charles Knight of the explosion of Mt. Peleé.

of the cloud suffocated the entire population (some 30,000 people) within minutes. There was one survivor in the city, a convicted murderer who was in a dungeon many feet below ground, awaiting execution. Days later, rescue parties led by a few people who had been on ships in the harbor heard his pitiful cries for help and dug him from his hole. As the sole survivor of the greatest instantaneous catastrophe in recorded history, he was shown no mercy, and the execution was carried out at an appropriate time.

11–7
Ocean trenches

Long, deep trenches cut into the sea floor between the island arcs and the flat deep-sea plains (Figure 11–14). On the eastern border of the Pacific Basin, the trenches are adjacent to the continent.

The deep trenches have depths that are as great as the thickness of the sedimentary rocks we've measured in the Appalachian Mountains. The Philippine, Mariana, and Japan trenches are 10,000 meters or more deep. One might theorize that the trenches near continents are places where geosynclines are forming. The earthquake and volcanic activities near them certainly indicate forces are squeezing the earth's crust. There must be deformation taking place there.

One problem arises, however, in considering the trenches as future geosynclines. They are already deep. No shallow-water sediments can form in them to make the rocks we are now so familiar with. Even so, it seems that

FIGURE 11–13
The locations of active and recently extinct volcanoes.

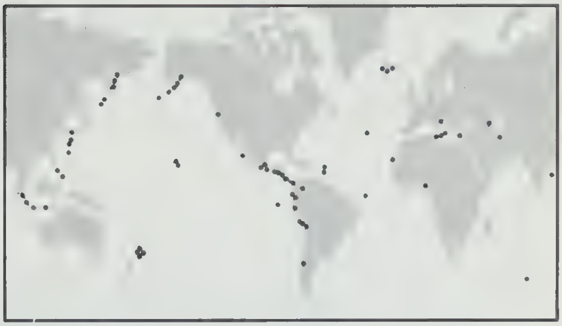


FIGURE 11–14
The world's island arcs and deep-sea trenches.

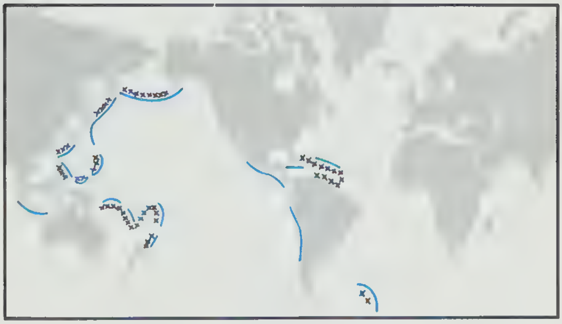
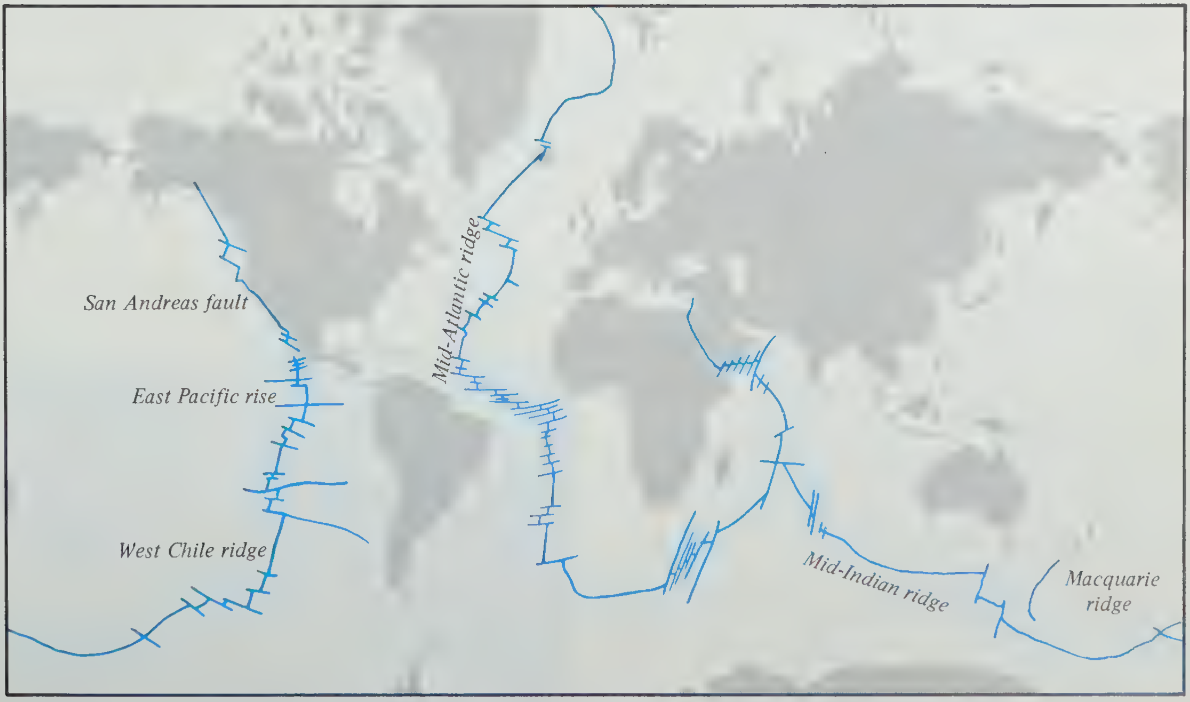


FIGURE 11–15
World distribution of oceanic ridges.



squeezing forces are pushing the crust down to form trenches. These forces must be like those that deform the geosynclines.

11–8
Mid-ocean ridges

In your Earthquake Watch, you saw another pattern of crustal activity. There are numerous focuses that form lines in the ocean basins. Here are also located the great **mid-ocean ridges,** the longest and tallest mountain ranges on earth (Figure 11–15). These submerged ridges wind across the floor of the ocean, following a path that is roughly midway between the continents. (This is best noted in the mid-Atlantic ridge.) In a few places, such as the Azores and Ascension Islands, parts of the ridges rise above sea level (Figure 11–16). The crest of most of the mid-ocean ridges are 6,000 meters above the sea floor; yet the tops still are submerged.

The mid-ocean ridges are volcanic. Vast volumes of lava have flowed through giant cracks or fractures and piled up on the sea floor. The eruption of the island of Surtsey in 1963 is evidence of continuing crustal unrest today.

Mid-ocean ridges have been found in the Atlantic, Pacific, and Indian Ocean basins. Soviet and American scientists working from drifting ice floes, and Americans in nuclear-powered submarines, have mapped a mid-ocean ridge in the Arctic Basin. All of these mid-ocean ridges, excluding the isolated Arctic ridge, form a single system 46,000 kilometers long.

In some places the ridges are broken by a series of cross faults that give them the look of a crude staircase (Figure 11–15). The ocean floor in such areas appears to be composed of blocks.

In 1953 a deep trench was discovered running alongside the mid-Atlantic ridge (Figure 11–17). Since then, similar trenches or sets of parallel trenches have been discovered and mapped elsewhere in the mid-ocean mountain system.

Mid-ocean ridges, geosynclinal mountains, and island arcs form as the crust of the earth moves. Geosynclinal mountains and island arcs are created by squeezing (compression). But the clearest idea is that the mid-ocean ridges and their trenches are caused by stretching (tension) in the earth's crust (Figure 11–18). The tensional and compressional forces, whatever causes them, should equal each other—at least over long periods of time. There is no evidence that the earth is either expanding or contracting.

11–9
Other crustal movements

In the ocean basins there are many peaks that are not part of island arcs or mid-ocean ridges. Thus, they don't fit the patterns of crustal movement discussed earlier, but they are worth a side glance. The Hawaiian Islands, for example, are part of a long chain that is not near

FIGURE 11–16
São Miguel Island in the Azores.

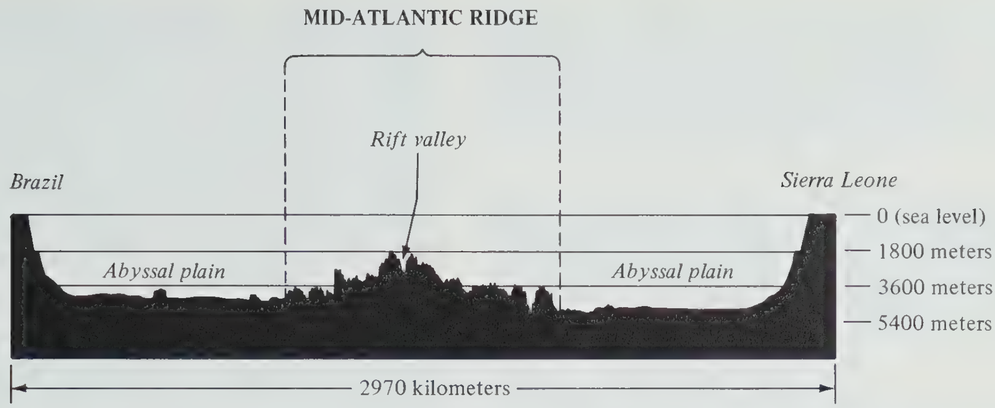
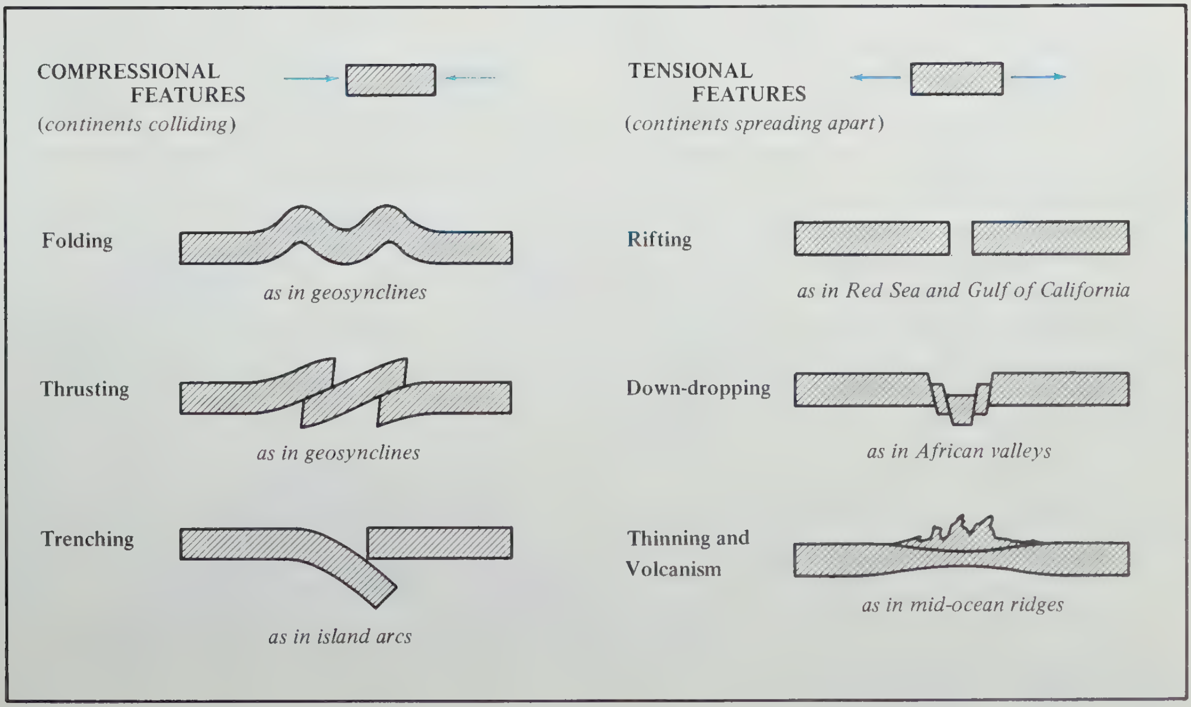
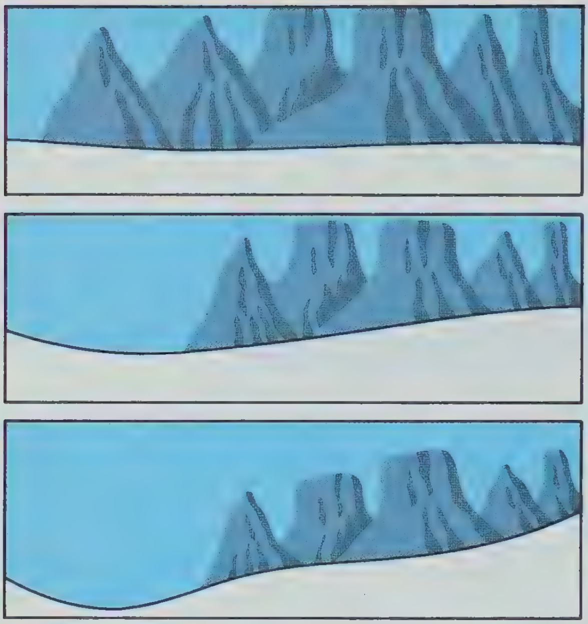


FIGURE 11–17
A profile of the ocean floor across the mid-Atlantic Ridge. The height of the ridge is exaggerated about 70 times.

FIGURE 11–18
The responses of the earth's crust to compressional and tensional forces





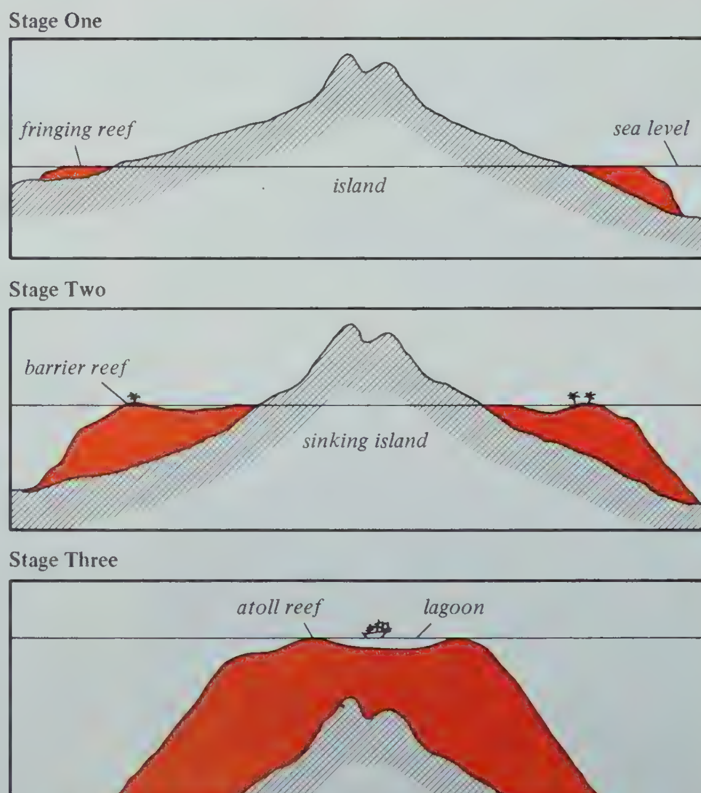


Figure 11–19
(left) Stages in the development of seamounts and flat-topped guyots in the vicinity of the Aleutian Trench.

Figure 11–20
(right) Coral animals grow together in huge colonies. Their skeletons form coral reefs.

Figure 11–21
(bottom) Stages in the development of coral atolls, based on drawings by Charles Darwin.

other volcanic mountains. Because these islands are really huge piles of lava lying on top of the sea floor, their great weight causes the crust to sink near the Hawaiian chain. Here there is motion in the crust without any compressional or tensional forces being active. The sinking goes on even while huge volcanic mountains such as Mauna Loa on the big island of Hawaii are growing. Even though these chains are not at mid-ocean regions of tension, they form at zones of weakness.

In addition to these great volcanic chains, there are thousands of isolated volcanic mountains and seamounts scattered across the deep-sea floor. Some have pointed peaks (Figure 11–19). Other seamounts probably had their tops eroded flat by ocean waves. However, their present depth is far too great to be explained by continuing wave erosion, even during the ice ages, when sea level was 100 meters lower than it is today. These flat-topped seamounts must have reached higher above the sea floor to or near sea level. A series of flat and pointed volcanic peaks near the Aleutian Trench off Alaska provides a clue to the formation of some seamounts.

Before the formation of the Aleutian Trench, the sea floor was flat and not pulled down into a trench. Some of the volcanic seamounts could have reached the surface. As the trench formed, the sea floor sank, not only in the trench but also for a considerable distance around it. This sinking of the sea floor would have lowered the eroded volcanic peaks in that area. The sinking was greatest near the trench. Figure 11–19 shows the present locations of the pointed and flat-topped seamounts in relation to the Aleutian Trench. It supports the idea that crustal sinking accounts for the present depths of those seamounts.

Coral reefs provide other examples of vertical movement in the crust of the Pacific Ocean. The coral reefs at Eniwetok Atoll in Micronesia were drilled to a depth of 1,400 meters. Cores showed the entire reef was made of coral skeletons. Corals are small animals that live only in shallow, warm waters. (See Figure 11–20.) Apparently, the surface water of these tropical seas has not changed for the past 60 million years, the time it took the whole reef to form. The question is how 1,400 meters of coral rock could be deposited in these reefs. Coral animals are known to live only in shallow water!

Charles Darwin visited coral atolls in the Pacific when he was 22 during the famous voyage of HMS *Beagle*. He was the first person to propose that the sea floor around the islands had slowly subsided. The corals grew upward, keeping pace with the lowering of the sea floor. Darwin identified three types of coral reefs, which he interpreted as three stages of development (Figure 11–21). He believed that atolls were shoreline reefs that had reached the last stage of sinking.

The publication of Darwin's ideas on atolls in 1842 started scientists arguing for a hundred years about his theory. The borings on Eniwetok in the 1950's reached volcanic rock after passing through the 1,400 meters of coral. These results faithfully supported Darwin's coral reef theory.

11–10 Stable and mobile regions

We can now return to the subject of overall patterns of movement in the earth's crust. Throughout geologic history, continental margins have been regions of earthquakes, massive deposition, and bending, folding, and faulting of the earth's crust. The margins are at the boundary between the continents and the ocean floor. So it seems logical to assume that these movements are caused by interaction between the continental crust and the oceanic crust. Scientists cannot tell whether the interface between the continental and oceanic crust is sharp or gradual. They do know, however, that the oceanic crust is composed of the dark-colored minerals that form basaltic rocks. The rocks of the continents are different. They are made of light-colored minerals having little iron but much silica. That is, the continental crust is granitic. The thickness of these two crusts also differs. The continental is up to six times as thick as the oceanic.

Another difference between the ocean and continents should be obvious from the Earthquake Watch. In mid-ocean there is crustal activity, but not in the middle of the continents. This pattern is consistent on all continents: the central portion is stable, the margins are mobile.

Every continent has a central core made up of the worn-down remnants of ancient. deformed rocks. The cores have undergone little deformation for hundreds of millions of years. Surrounding the cores are lowlands underlain by nearly horizontal beds of sedimentary rocks (Figure 11–22). These layers are thin where they lap over the edges of the ancient cores. Toward the continental margins they thicken and grade into the deformed rocks of geosynclinal mountains, as we saw on the James Hall field trip. Beyond the mountains lies the great wedge of younger sedimentary rocks that make up the coastal plains and continental shelf.

The ancient rocks in the central core are so deeply eroded that the land is nearly flat. If we examine them closely, however, we see that they are as deformed as the rocks in the Appalachian Mountains. These eroded remains are really inactive, geosynclinal mountains formed in earliest geologic time.

The first stage in the growth of continents seems to be the deposition of a continental margin against the edge of a small core.

Figure 11–22
A cross section of a model continent.

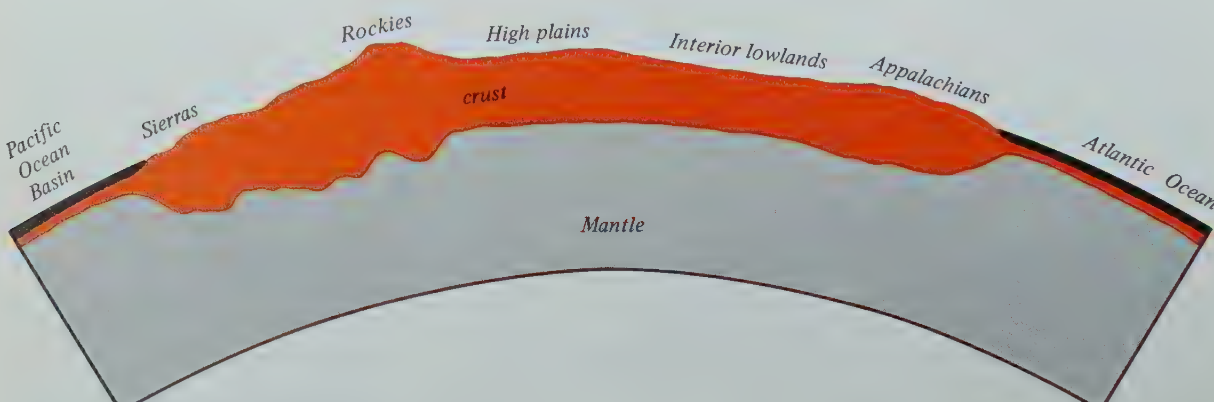


Figure 11–23
The coasts of the continents fitted together at a depth of 900 meters. Why weren't the continents matched at sea level?

Compressional forces squeeze the margin into a belt of geosynclinal mountains. They in turn are eroded to form a new continental margin. So the continents grow, with continental margins being added like growth rings on a clam.

11–11 From continental drift to sea-floor spreading

Alfred Wegener, a German scientist of the early 20th century, thought that the east coast of South America could fit against the west coast of Africa like pieces of a jig-saw puzzle (Figure 11–23). He reasoned they must have once been together! When they split, the Mid-Atlantic Ridge was formed as a remnant, and the two continents drifted away from each other. He logically called his concept "continental drift."

Wegener's ideas were popular for a number of years because there was supporting evidence that Africa and South America had similar rocks and fossils. But there were a number of unsolved problems. What were the forces that caused the drifting? If the continents were moving apart, there would be compressional forces only on the west coasts of North and South America. Yet we've noted the results of compression in the Appalachians. What caused that? These and other questions were not easily answered, so continental drift was placed on the back burner for several decades.

Surplus materials from the United States Army following World War II provided a new way to study the oceans' crust. Great volumes of high explosives had been stockpiled. Taking advantage of the surplus, a few scientists began to drop explosives from research vessels (Figure 11–24). The sound waves traveled through the water, the sea floor, and the rocks beneath the sediments. A second ship stationed a few miles away recorded the arrival of the sound waves, just as a seismograph on land records the arrival of earthquake waves.

From this windfall of surplus explosives, oceanographers learned that Alfred Wegener was partly right. There was evidence that the continents were moving. Not only that, the evidence indicated that the sea floor was moving as well—away from the mid-ocean ridges toward the continents. This discovery called **sea-floor spreading,** seemed to answer many of the questions that were left dangling bv the earlier idea of continental drift.

The image of the sea floor's actually moving from the center of an ocean basin toward the

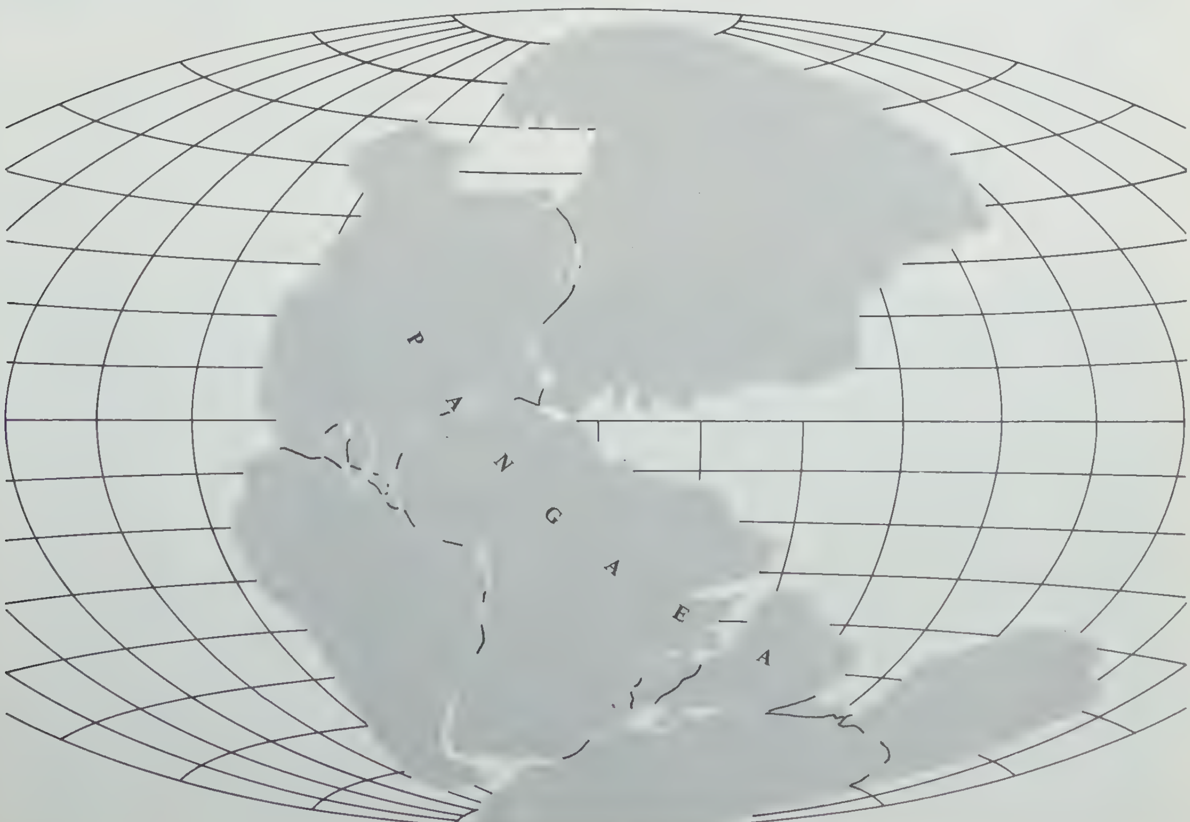
Figure 11–24
An oceanographer pushes 200 pounds of TNT overboard. The explosion will produce data about the structure of the sea floor.

bordering continents was tremendously exciting. Scientific expeditions set out to obtain data on the ages of sea-floor rocks, heat-flow at the mid-ocean ridges, and the way the oceanic crust met the continental margin. By the mid-1960's, the oceanographers had made the following important discoveries:

1. Greater amounts of heat come through the mid-ocean ridges than other parts of the earth's crust.
2. The greater the distance from the mid-ocean ridges, the older the rocks are.
3. The oldest rocks known in the ocean's crust were formed about 150 million years ago (only 1/20 of the age of the oldest rocks on the continents).
4. The youngest rocks are being formed continuously, as on the island of Surtsey.
5. The oceanic crust is forced down beneath the continental margins.

By amazingly careful calculations, scientists determined that the sea floor is spreading at an average rate of about two centimeters per year. That is, therefore, the growth rate of new crust from mantle rock. The rate of destruction of old crust must be the same. The old crust is being destroyed when it is forced down into the mantle at the continental margin.

FIGURE 11–25
Pangaea, as it might have looked 200 million years ago.



11–12 The plates of the earth's crust

Amidst all of this excitement over sea-floor spreading, we were learning many details of the crustal structure. Not all of them fit a simple spreading picture. For example, some portions of the sea floor were apparently moving faster than others. Also, in some places the spreading was within the continental block (as in the Red Sea and the Gulf of California), not the ocean's crust. Finally, there was increasing evidence that all the continents had once been together, like the "Pangea" suggested by Wegener (Figure 11–25).

The pieces of the puzzle began to fit by the late 1960's. Scientists in the United States realized that all their earlier questions could now be answered with the following three-part theory:

1. There is a series of convection cells in the earth's mantle (Figure 11–26).
2. Spreading occurs at the rising parts of the cells and compression at the sinking portions.
3. The earth's crust is composed of six huge "plates" that moved apart from a center. The plates are the tops of the convection cells. The plates include the six continental masses and adjacent sea floors. Within the major plates are smaller crustal segments (sub-plates) that move at different rates because of variations in the convection cells (Figure 11–27).

Any large movements of the earth's crust are called **tectonic movements** by geologists. Therefore, the concept of crustal plates in motion has been given the name **plate tectonics.**

The picture we have now of the earth's crust is that of strong, rigid plates, all in motion. The boundaries of the plates produce the action: the earthquakes, the volcanoes, and the mountain ranges. Where the plates are separating, new crust is being formed (the mid-ocean ridges). At the side boundaries, the plates are sliding past one another. There may be faults and earthquakes, but no crust is being formed or destroyed there. Such a series of faults occurs across the mid-Atlantic ridge at the equator.

Where the plates are colliding, crust is being destroyed or changed. These boundaries form the deep-sea trenches, island arcs, and the mountain ranges. So, we've finally learned the source of the forces that form the geosynclinal mountains!

Thought and Discussion

1. Why do earthquakes show areas of crustal activity?
2. How are volcanoes related to deep ocean trenches?
3. What is the difference between mid-ocean ridges and geosynclinal mountains?
4. How does the stability of ocean basins and continents differ?
5. How do the ideas of continental drift and plate tectonics differ?

Unsolved Problems

The concept of plate tectonics was considered in 1972 to be the most exciting and valuable idea about the earth to be conceived in a hundred years. If further studies support the concept, then we may someday have information to help accurately forecast earthquakes and volcanic eruptions around the world.

As with any concept as grand as that of plate tectonics, many details of the structure in the earth's crust seem at this time not to fit neatly within the scheme. Where the plates come together, creating trenches and squeezing geosynclines, the great sedimentary layers are said to be pulled deep within the crust beneath the continent. We must conduct more studies to learn whether this actually happens. Off the east and Gulf coasts of the United States, off the great trenches of the Pacific basin, and off Indonesia, it seems to be so. But it seems not to be taking place off the west coast of the United States and South America. Yet there is volcanic activity and many earthquakes along these continental borders.

The rate of movement of the plates is determined by measuring changes in the earth's magnetic field. Much of the oceanic crust has reversals that fit very well. But some areas, such as around Hawaii and the Fiji Islands, have differences that do not fit the plate movement pattern.

Figure 11–26
Convection cells may flow through the upper mantle.

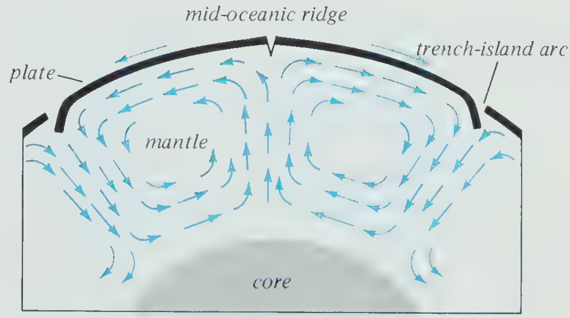
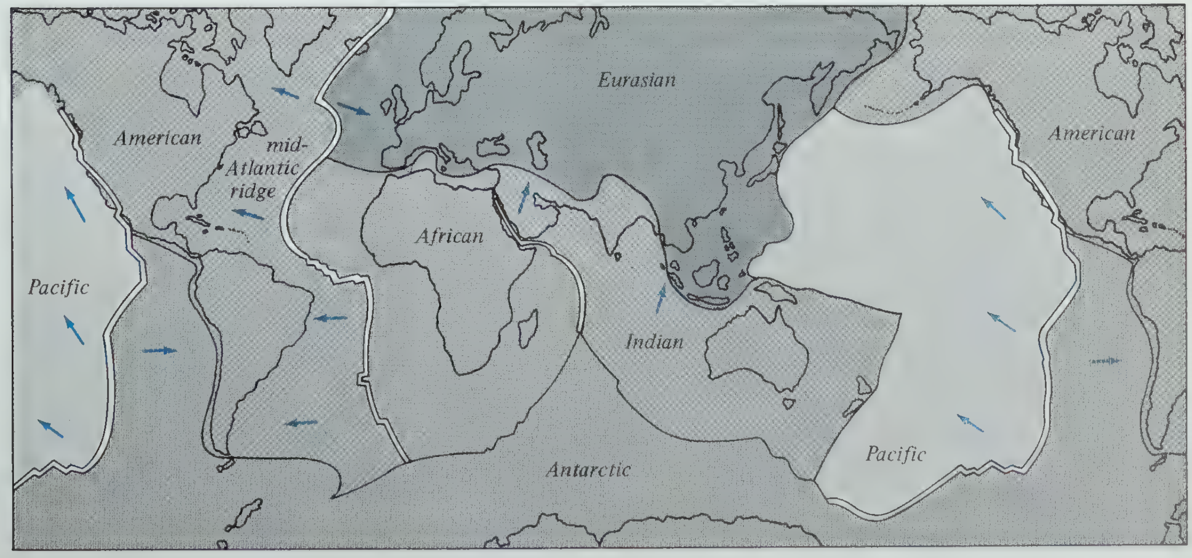


Figure 11–27
The six major crustal plates.



Chapter Review

Summary

Rocks in the major mountain ranges were originally deposited in a geosyncline. All the layers of sediments show some evidence of originating in shallow water. Modern geosynclines form along the borders of continents. They are composed of the continental shelf, the slope, and the rise. The thickest deposits are on the rise, and their great weight tilts the continental margin toward the ocean basin.

Rocks within the geosyncline are bent, broken, and deformed into mountains by pressures within the crust. The breaking and bending of the rocks also causes the earthquakes that are so frequent in regions of active mountain building. Earthquakes are usually of such low energy that only sensitive instruments can record their passage. When strong earthquakes occur, the whole world may learn about them.

Volcanoes are also evidence of great pressures and movements deep within the earth's crust and mantle. They are most active along ocean borders and on mid-ocean ridges. The ridges make up the longest and tallest mountain ranges on earth. At the ridges, new crust is being formed as the old crust is pulled apart and lava pours out on to the sea floor.

The most mobile parts of the earth's crust are in the ocean basins and where ocean and continents meet. Central parts of continents are now stable. They are the ancient cores around which geosynclinal deposits have developed and built up the earth's land masses.

The evidence of mountain building and volcanic action indicates that great segments of the earth's crust have been, and still are, moving. Early scientists thought continents were "drifting." But we believe now that convective cells in the earth's mantle are driving the crustal plates around. The movement of the plates produces squeezing and stretching forces. These forces create geosynclinal mountains, ocean trenches, island arcs, and the mid-ocean ridges.

Questions and Problems

A

1. What evidence suggests that geosynclinal sediments have been deposited in shallow water?
2. What features of the Gulf of Mexico Basin lead some scientists to believe that it is an active geosyncline?
3. What is the geosyncline theory?
4. How do you know that rocks have been deformed?
5. Describe the features of a folded mountain range.
6. What is a fault? Describe the various motions that may be associated with the formation of a fault.
7. Where on the continents are geosynclinal mountains generally located? Where in the oceans are island arcs generally located?
8. Where is a mid-ocean ridge not a mid-ocean ridge?
9. What are the different kinds of coral reefs and how do they form?

B

1. In a geosynclinal basin, where does most of the rock deformation take place? Describe the conditions and the changes caused by these conditions.
2. Where does the energy that causes earthquakes come from?
3. What evidence indicates that island arcs may be a middle stage in the formation of geosynclinal mountains? What evidence rules against this idea?
4. What should happen to the crust of the earth where volcanic islands are growing?
5. Give a possible explanation for the development of mid-ocean ridges and trenches.
6. Why are the mid-ocean ridges not believed to be the result of compression?
7. How did the tops of seamounts become eroded if their present level is far below the lowest possible level of the oceans?
8. How is it possible to find corals at a depth of 1,400 meters when coral does not form below a depth of 80 meters?
9. Describe the difference between materials in the continental and oceanic crusts. How do we know about this difference?
10. How do the water cycle and the rock cycle work together?

C

1. As sediments move from high areas into geosynclinal basins they lose potential energy. So does the water that moves them. What is the source of the potential energy of the sediments and the water?
2. Under what conditions would the remains of animals that had lived on land be found in sea floor deposits?
3. Besides the weight of the sediments, what other force probably aids in the subsidence of geosynclines?
4. What finally causes the uplift of these deep geosynclinal rocks?
5. Describe the processes that could someday make the East Indies and Japan a part of the Asian mainland.

Suggested Readings

Bates, R. L., and Sweet, W. D., *Geology*. D. C. Heath & Co., Boston, 1966.

Darwin, Charles, *The Voyage of the Beagle*. Doubleday & Co., (Anchor Books), Garden City, New York, 1962. (Paperback)

Heller, R. L., *Geology and Earth Science Sourcebook*. Holt, Rinehart & Winston, Inc., New York, 1970, Chapters 2, 3, and 4.

12. Rocks Within Mountains

The great mountain ranges on the continents came from the sea. Where a mountain range is now, there was once a geosyncline. As much as 20 kilometers of sediments were deposited, then folded and faulted into mountain ranges. This is briefly the account of mountains from the sea presented in Chapter 11. It suggests that if you examine the rocks exposed along rivers or roads through high mountains, you will find only sedimentary rocks.

This, however, is not true. Half Dome, shown on the facing page, is part of the Sierra Nevada. It is granite. In any great mountain range you can see an abundance of igneous and metamorphic rocks. In fact the great bulk of all three kinds of rocks have their origin in the mobile belts of the earth's crust.

First the sedimentary rocks are thrown into contorted and broken patterns. Then molten rock material deep in the crust rises to the level of the action. Soon there is a period of quiet but vigorous erosion, after which great volcanic cones rise to dominate the mountain scenery. Finally the volcanoes become extinct. Erosion proceeds with the task of removing the mountains grain by grain to be deposited in yet another geosyncline.

Plutonic Rocks

12–1
A young mountain range

Western Montana is an area of high, rugged mountains like those in Figure 12–1. Along the Continental Divide there are many peaks higher than 3,000 meters. The peaks and ridges rise 750 to 1,500 meters above the valley floors. Glaciers once nestled in valley heads around many of the peaks. The rocks exposed here are typical of those found in young, complex mountain ranges. In old mountain ranges the sedimentary rocks are gone, and only igneous and metamorphic rocks remain.

Sedimentary rocks accumulated over a very long time in this area to a total thickness of about 9,500 meters. There was one significant break in deposition. But the older rocks were hardly disturbed before deposition started again. Finally, the region was intensely folded and faulted. Erosion produced the rugged scenery so typical of the Rocky Mountains. This erosion may have removed as much as 2,000 meters of rock at some places! The igneous and metamorphic rocks formed during and after the deformation are exposed at many places. Such rocks form the bedrock over thousands of square kilometers.

12–2
Using a geologic map to study rocks

The Philipsburg area is about half way between Butte and Missoula, Montana. The geologic maps on pages 262–3 show the distribution of rocks at the surface or under the soil cover. The types of rocks and their relative ages are shown in the legend. The oldest rocks are at the bottom of the legend and the youngest at the top.

PROCEDURE

Examine the map. How would you describe the pattern of distribution of the sedimentary

FIGURE 12–1
High mountain scenery in the Rocky Mountains of Colorado.

rocks? "Confused" might be the first word that comes to mind, but can you do better in one or several words? How can layered rocks occur as bands?

Notice the heavy black lines like those just north of Philipsburg. These lines mark the faults at the surface of the earth. The fault planes extend below the surface for a considerable, but usually unknown distance.

Most fault planes are not really flat planes but are gently warped surfaces that are inclined from the horizontal at steep angles. The map symbols point in the direction that the fault tilts downward from the surface.

1. *If rocks are displaced by faults, might faults displace faults?*
2. *Look at the fault lines north of Philipsburg. Some run almost north-south, others more nearly east-west. Which set do you think is younger?*
3. *Some of the faults shown shift the boundary lines between various sedimentary rock layers. Does this mean that the faults are older or younger than the rocks?*

The rock masses labeled P-3 through P-8 in Figure 12–2 are called ***plutons.*** *This name is derived from Pluto, the Roman god of the underworld. No one has ever seen a pluton form. All of the evidence we have indicates that these masses form below the surface within the growing mountain range. They are not known to develop in any other environment.*

4. *Look at the somewhat round area of rock labeled P-3 just east of Philipsburg. Does this rock cut across or parallel the units of sedimentary rock?*
5. *Would you conclude that this rock is older or younger than the sedimentary rocks it touches at the surface?*
6. *Would you conclude that P-3 is older or younger than the faults?*
7. *Notice that P-3 is not shown in the legend of the map. Where would you put it in the legend?*

12–3
Plutons

Figure 12–3 is a vertical cross section to a depth of 2,000 meters along the line W-E on the map. Notice that the sides of Pluton-3 are inclined steeply. The bottom of the figure is not the bottom of the pluton. It extends deep into the earth. The boundaries of P-3 cut across the sedimentary layers on both the western and eastern sides. It is clearly younger than any of the sedimentary rocks in the area. It is also younger than the folding and faulting.

The map shows several other plutons. Rock bodies of this type are common in folded mountain systems. All these rock masses have the same relation to the sedimentary rocks and the faults. They are numbered differently to indicate different chemical and mineral compositions.

The thickness of the roof of older rocks eroded from the top of the pluton is usually unknown (perhaps unknowable). In some instances it can be estimated. Estimates vary from as little as 1 to as much as 8 or 10 kilometers.

The Philipsburg pluton is modest in size compared to many. Most of the larger plutonic bodies in North America range from 4,000 to 50,000 square kilometers in area. One of the

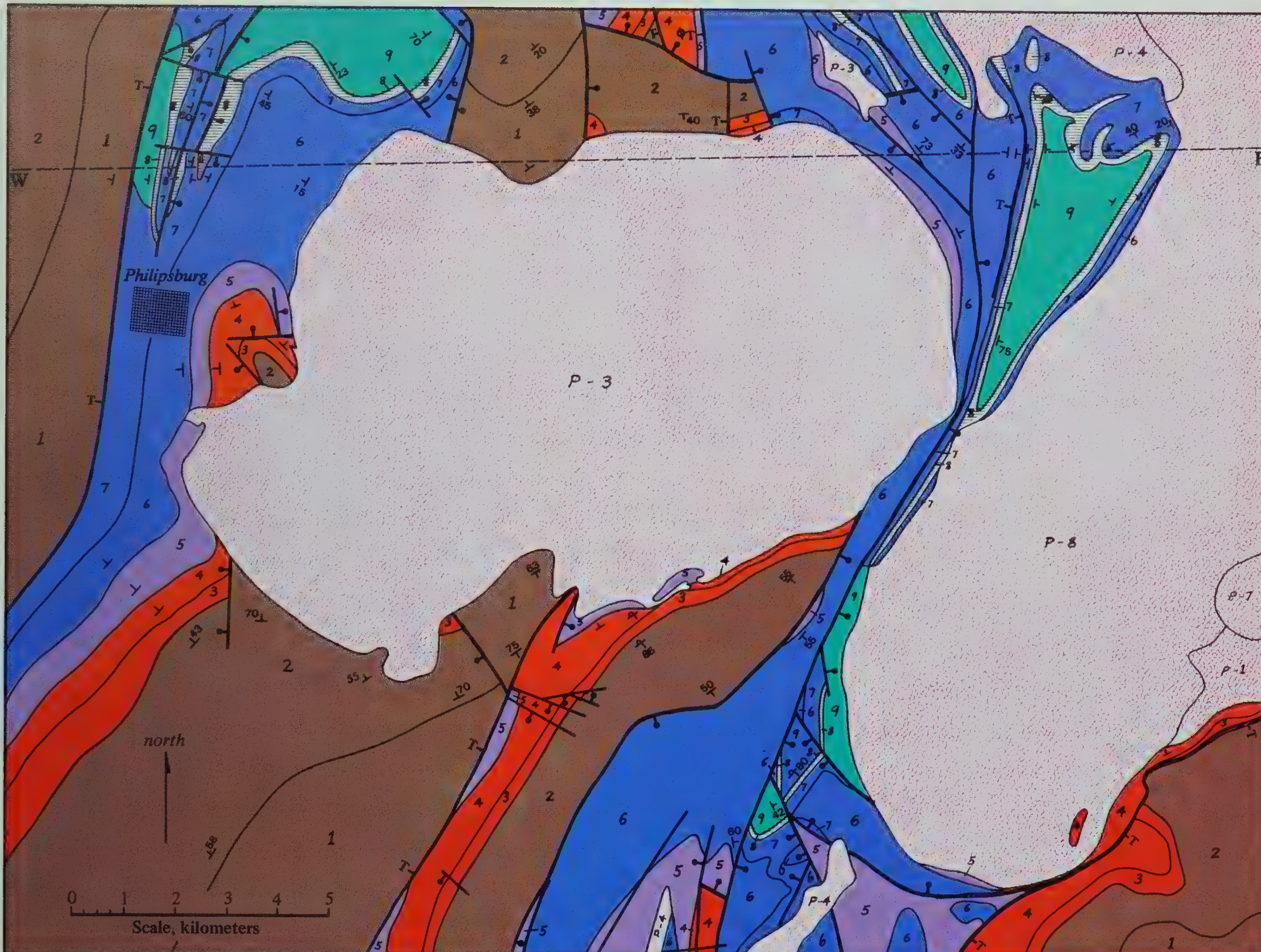
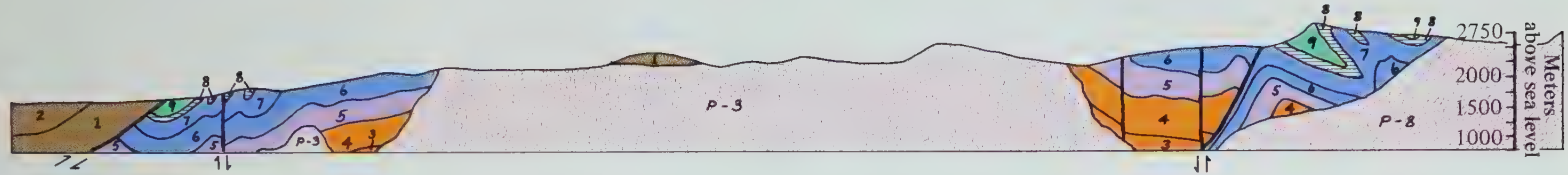


FIGURE 12–2



Legend

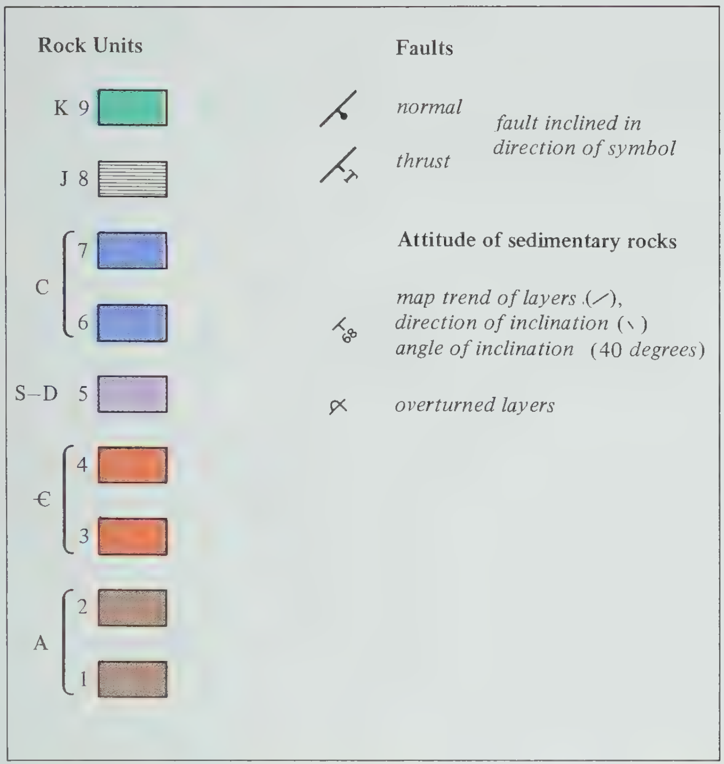


FIGURE 12–2
A geologic map of the area near Philipsburg, Montana.
FIGURE 12–3
A cross section along the W-E line in Figure 12–2.

largest in the world is in the Coast Range of British Columbia. It is 2,000 kilometers long with an average width of about 120 kilometers. This pluton is exposed over an area of 186,000 square kilometers. It is almost certainly not as deep as it is wide.

Most plutonic masses are elongated parallel to the mountain system they occur in. A typical large plutonic mass, such as the one in British Columbia, is a complex of smaller plutons. At deeper levels in the crust the plutons in the Philipsburg area probably join to form such a complex elongated parallel to the mountain range.

12–4
Investigating plutonic rocks

The rocks of the plutons are unsurprisingly called ***plutonic rocks.*** *They are a variety of igneous rock that forms below the earth's surface. They are more specifically known as* ***intrusive igneous rocks,*** *having intruded into existing rock layers. Plutonic rocks are varied in chemical and mineral composition but within small limits. Most are coarse-grained aggregates of feldspar and quartz-granite. They are generally light-colored (shades of pink and gray).*

About 60 per cent of a granitic rock is feldspar, the most abundant minerals in the earth's crust. Quartz is next in abundance and amounts to 30 to 35 per cent. The remainder consists of chain or sheet silicates, which are usually black.

There are rare plutonic rocks that are not granitic in chemical and mineral composition. These basaltic plutonic rocks are dark-gray or black. They consist mainly of gray feldspar and chain silicates.

Procedure

Examine specimens of plutonic rocks and separate them into two groups: light- and dark-colored. Dark colors are dark-gray and black only.

1. *How many specimens do you have in each group?*

Examine the light-colored specimens. Separate these specimens on the basis of color and texture (grain size). Describe each rock in your own words including variations in color and texture.

Look at the light-colored rocks with a low power lens. Try to identify feldspar and quartz in each of them. Feldspar will be pink, white or light gray, or a combination of these colors. It will show flat shiny faces. Quartz will usually appear as gray glassy grains without flat shiny faces.

2. *Try to estimate the relative percentages of feldspar and quartz in each of the rocks.*

Examine the black grains with the lens. If any flake off when you press a pin or needle against them, these are mica. The others are probably amphibole.

3. *Try to estimate the percentage of black grains.*

Now, turn your attention to the darker rocks. Separate and describe these as you did the light-colored rocks.

4. *Can you easily distinguish the feldspar from the black minerals?*

5. *Try to estimate the percentages of feldspar and black minerals.*

When you finish, ask your teacher to give you the names of the rocks in each group.

Thought and Discussion

1. Estimate the area of the pluton just east of Philipsburg. If it extends downward to a depth of five kilometers, what is its volume?
2. Assume the molten mass surrounded by cooler sedimentary rocks had a temperature of 800°C. How long would you estimate it would take the pluton to cool to 100°C? Recall that heat may move by radiation, convection, or conduction. Which of these would be most important in the cooling of a pluton?
3. Would you suspect that the slow cooling of a pluton affects the texture (grain size) of the rock which forms? Did some of the plutonic rocks you examined differ from others in average grain size? How would you explain the differences.
4. Can you suggest a reason for the much greater abundance of granitic rocks compared to basaltic rocks in plutons?

Metamorphism

12–5
Metamorphic rocks

Metamorphic rocks also form within mountains. In fact, typical metamorphic rocks do not form in other environments. In this respect they are similar to the plutonic rocks. These two kinds of rocks are closely related in time and place of origin.

Remember that metamorphic rocks are rocks that have been changed into new forms by high temperatures and pressures. This process occurs deep in the earth at temperatures and pressures that are higher than those on the surface, but not high enough to melt the rocks.

The graph in Figure 12–4 shows that the temperature of the earth increases with depth. The temperatures represented by the solid line on this graph are averages of measurements made in deep drill holes. The dotted line gives a prediction of temperatures at greater depths.

Pressure also increases with depth. Imagine yourself down several kilometers in a mine. How many tons of rock do you think might be over your head? Besides the thickness of the rock above you, what else would you need to know in order to calculate the pressure of the

FIGURE 12–4
Temperature increases with depth within the earth. The temperatures along the dotted lines are estimated.

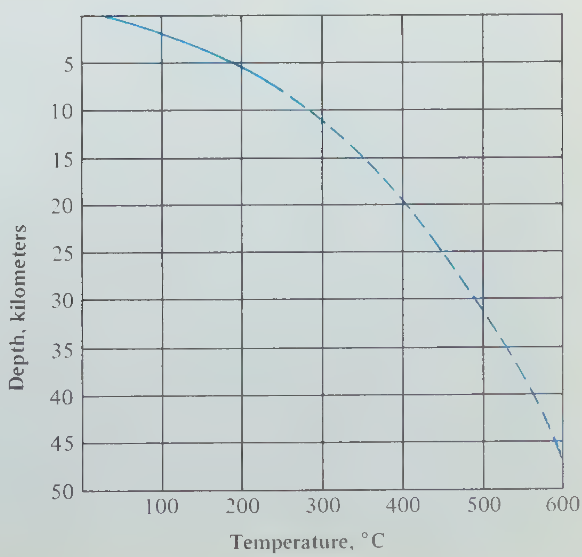


Figure 12–5
(top) Which of these rocks is metamorphic?

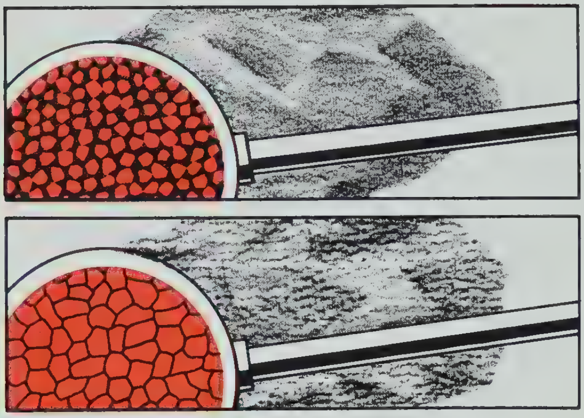
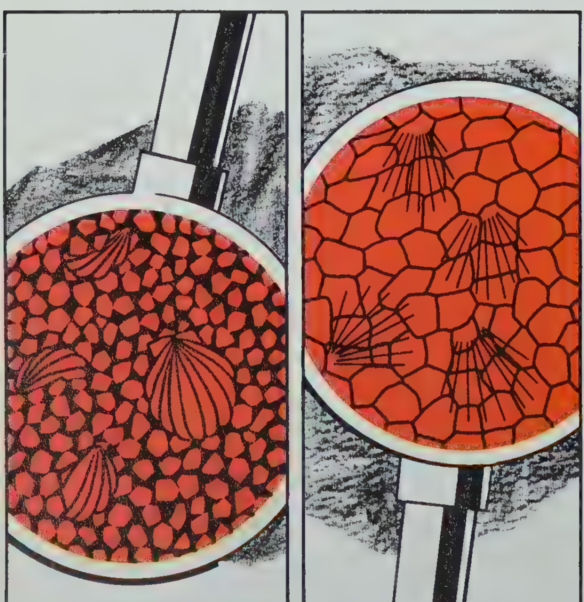


Figure 12–6
The rock on the left consists of quartz grains (SiO_2) and shells of scallops ($CaCO_3$). The rock on the right consists of wollastonite ($CaSiO_3$) and quartz. Which rock is metamorphic and which is sedimentary?



overlying rock (measured in kilograms per square centimeter or pounds per square inch)? If you put a rock specimen under great pressure on all sides at once, how could the rock change in order to occupy less space?

Look closely at the two rocks in Figure 12–5. Both rocks are made of quartz. One is a sedimentary rock called sandstone. The other is a metamorphic rock called quartzite. What differences can you detect between them? Which is the metamorphic rock and which the sedimentary rock? What features of the rocks influenced your choice? The kind of change shown in this figure occurs in almost all metamorphic processes.

Another kind of change is shown in Figure 12–6. Which of these pictures is the sedimentary rock and which the metamorphic? What kinds of changes have occurred? Have new minerals been formed? How do these examples differ from the rocks in Figure 12–5?

If you heated a piece of quartz sandstone in a hot laboratory oven to a temperature just below its melting point, changes would begin to occur. Changes in grain size and the growth of new minerals take place slowly, however. If you cooled the sample after a short time, you would see little or no effect of heating. Probably you would have to leave the sandstone in the oven for many months or even years to notice a change. A faster method would be to seal the sandstone in an airtight container and squeeze it intensely on all sides while you heated it. If there were a small amount of water in the sealed container, the modification of mineral grains and the growth of new minerals would be even faster.

Although high temperature and pressure are important in causing metamorphism, some rocks have been buried several kilometers below the surface without being changed. Remember that minerals contain ions. During metamorphism, some ions break loose from the minerals. For ions to move far in solid rock, small amounts of water or other fluids must be present. Therefore, rocks that have been deeply buried for a long time undergo less metamorphism if little or no water is present.

During metamorphism, ions rearrange themselves to occupy less space than before. The rock becomes denser. In Figure 12–6 some of the silicon ions joined with calcium (Ca) and carbonate (CO_3) ions to form a new mineral, wollastonite ($CaSiO_3$). Wollastonite is denser than the original calcite ($CaCO_3$). A sandstone containing shells ($CaCO_3$) can undergo a similar change and become denser. The change involves the disappearance of one mineral, calcite, and the appearance of another, wollastonite.

The two sandstones shown in Figures 12–5 and 12–6 are the parent rocks of the two quartzites. Each kind of sedimentary or igneous rock may become a metamorphic rock. The chemical elements that are present in a parent rock determine the kinds of metamorphic rocks that can form from it.

12–6 Metamorphism varies with rock environments.

Different kinds of metamorphic rocks are formed under different conditions. Each combination of heat and pressure can produce another kind of metamorphic rock. The most important factors in metamorphic environments are temperature, pressure, and the amount of water.

Metamorphism *can* take place at the earth's surface. Imagine a red-hot stream of lava spilling out of a volcano. As lava flows over the top of other rocks, it may bake them. Baking of this type is called **contact metamorphism** because it occurs when molten rock comes in contact with another rock. The minerals in the cooler rock change in composition and structure. A zone of contact metamorphism is shown in Figure 12–7.

Figure 12–7
A light-colored layer of basalt atop a layer of metamorphosed sedimentary rock called hornfels.

Some bodies of molten rock exist deep below the earth's surface. This molten material is called **magma.** The great heat from this material also causes contact metamorphism. The amount of change in the solid rock depends on the temperature of the molten material. More important, the amount of change depends on how long the molten material is in contact with the surrounding rocks.

A lava flow on the earth's surface cools rapidly and does not have time to do much baking. But the great heat from a deeply buried body of molten rock material such as a pluton cannot escape to the air. This heat can only escape through the rocks surrounding the molten material. The molten rock may take thousands or hundreds of thousands of years to cool. In such long periods of time many metamorphic changes may occur in the surrounding rocks.

The sedimentary rocks surrounding plutons are pre-heated by deep burial. Folding has also increased the pressure. As the heat slowly flows outward from the plutons, rocks may be changed as far as three kilometers from the contact. When erosion of the mountain range reaches the level of the plutons, metamorphic rocks are observed over hundreds or thousands of square kilometers. This long distance change is called **regional metamorphism** in contrast to the more local effects of contact metamorphism.

If the magma contains water, solutions of ions can be forced outward into the surrounding rocks. Near the pluton these solutions may deposit ores of gold, silver, copper, lead, zinc, and other metals. This is the environment in which most ores form. Farther from the pluton,

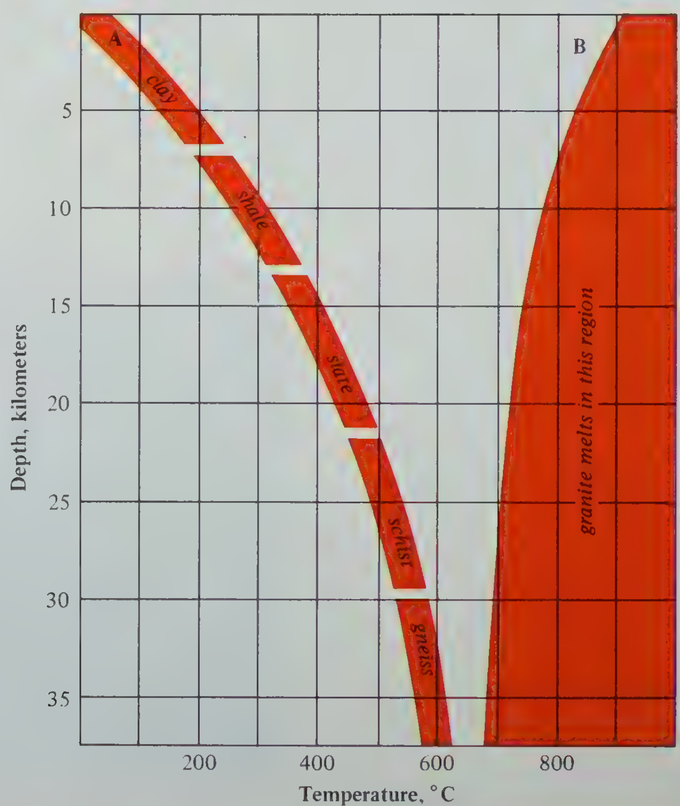


Figure 12–8
Curve A shows the approximate zones beneath the crust at which different rocks are metamorphosed. Granitic rocks melt at the temperature and depth conditions to the right of curve B.

the solutions may provide water which will speed up the regional metamorphism.

Metamorphism can also take place without plutons. As the thick pile of sediment in a geosyncline accumulates, the area sinks. Sediments in the lower part are slowly carried deeper and deeper into the crust. Temperature and pressure continue to increase. The changes that would occur in a layer of clay in a sinking geosyncline are shown by curve A in Figure 12–8.

According to the diagram, what might happen to the rock if it were pushed down much below 35 kilometers? What would happen if the temperature at a depth of 30 kilometers were 150 or 200 degrees hotter than the temperatures shown by curve A?

Rocks become denser as their environment becomes hotter and as pressure increases. The density of the various rock types shown in Figure 12–8 increases from clay through shale, slate, schist, and gneiss. In rock environments where schist and gneiss form, the temperatures and pressures are great enough for denser minerals such as garnet to begin to grow.

The temperatures and pressures shown in Figure 12–8 are based on laboratory experiments. If the experiment is like the conditions in nature, it should be possible to work backwards. That is, we should be able to look at a metamorphic rock and gain some idea of the environment in which it formed. For all rock environments to the right of curve B in Figure 12–8, the common rocks in the crust can no longer exist as solids. They begin to melt. Once rock material has melted completely, it can later solidify to form different kinds of igneous rocks. However, only partially melted rock is also capable of flowing and producing new rock bodies.

12–7 Investigating metamorphic rocks

Examine specimens of sedimentary rocks such as shale, sandstone, and limestone. Compare these with the metamorphic rocks which commonly form from each. Shale will be changed to slate, shist, or gneiss depending on the conditions of metamorphism. Sandstone will be changed to quartzite, and limestone to marble. All of the typical metamorphic rocks will show variations. These variations will depend on impurities in the parent rock and the condition of metamorphism.

Procedure

Describe each metamorphic rock in your own words.

1. *How do these rocks differ in texture and mineral composition from the sedimentary rocks?*
2. *If you have more than one specimen of any of the metamorphic rocks, how do they differ from each other? How would you explain these differences?*
3. *Plutonic rocks may also be changed by metamorphism. Do you have any metamorphic rocks you think may have originally been granite? If so, what evidence indicates this origin?*

12–8 The origin of granite

Figure 12–9 shows the temperatures at which granite containing no water melts. The melting temperature depends on the depth it is buried in the earth. At what temperature would granite begin to melt at the earth's surface? At what temperature would it begin to melt at a depth of 12 kilometers? According to the graph, all the granite does not melt at exactly the same temperature. Can you think of a reason why not?

The results of heating granite containing a little water (and most do) are also shown in Figure 12–9. How does the melting temperature change with depth? Probably small amounts of water are present everywhere in the crust. (If this is true, is deep magma likely to remain melted at lower temperatures than surface lava? Why?)

When the boundary of a granite body cuts sharply across the rocks around it, geologists generally agree that it was probably squeezed in as magma. Most granitic magma comes from the melting of sedimentary and older granitic rocks deep in the roots of mountain chains. Once the magma has formed, it may be squeezed up to higher levels where it cools and solidifies. Other bodies of granitic magma may remain where they are formed and cool more slowly.

Suppose that a group of sedimentary rocks sinks deeper into a geosyncline. Temperature and pressure gradually increase, and the amount of metamorphism of the rocks also increases. Look back at Figure 12–8 and notice that the two curves approach each other. Therefore, the same minerals could form by metamorphism of sedimentary rock or solidifying of granitic magma at only slightly higher temperatures. So, it has been proposed that some granite forms by very intense metamorphism just short of much, if any, melting.

Many large granite bodies merge gradually into intensely metamorphosed sedimentary

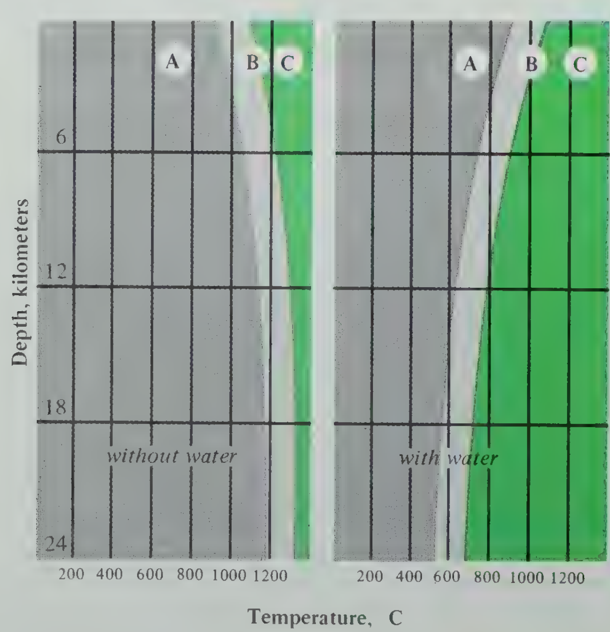


FIGURE 12–9
The temperatures at which granite melts depend on whether it contains water. In the shaded areas (A) it is solid. In (B) melted partially, and completely melted in (C).

rocks. Their interface is difficult to define. The texture and mineral content of the rock may be just like the texture and mineral content of a granite formed by igneous processes. Therefore, it is not always possible to determine whether a rock that formed deep below the surface is igneous or metamorphic.

If you know the exact make-up of the granite and its relationship to other rocks in the area, you can make a reasonable guess about its origin. But two geologists can study the same body of granite, observe the same relationships, and still disagree on whether the granite formed when a melt solidified or whether it formed by intense metamorphism. It is important to distinguish between what you actually see in rocks and what you infer about their origin.

Thought and Discussion

1. Find out how ordinary bricks are made. In what ways does the manufacture of bricks resemble metamorphism?
2. At one time weathering was considered to be a special kind of metamorphism. Why do you suppose this was done? Why is it no longer done?
3. Do your observations suggest a gradual change in texture in the metamorphic series from shale to gneiss? How would you explain the presence or absence of such change?
4. A schist formed at great depth near a pluton may be brought to the surface very slowly by erosion. Such rocks commonly show changes in mineral composition and texture. Would you consider these changes to be metamorphism?
5. The discussion of metamorphism emphasized temperature, pressure, and solutions as important factors. Can you suggest another factor which should be included?

Volcanic Rocks

12–9
Rocks upon mountains

The final rock-making event in a mobile belt is volcanism. First plutonic and metamorphic rocks form, and extensive erosion occurs. Then volcanoes may appear on the eroded surface of the mountain system. The total time from the beginning of folding to the end of volcanism may be as much as 30 million years. Remember that great changes have occurred, and 30 million years is not long in geologic time.

The volcanism in mobile belts includes the formation of great volcanic cones and, in some instances, the construction of broad lava plateaus. Volcanoes form over and around the opening of conduits that carry lava to the surface. The volcanic cones are composed of materials erupted from the conduits. They may be 4,000 meters high with a base covering tens of square kilometers.

Lava plateaus develop where lava reaches the surface through a multitude of fractures. The lava spreads out in great sheets, first filling the valleys and then covering all the broad expanses except the highest hills. The transfer of great volumes of lava from beneath the crust to the surface may cause the crust to subside.

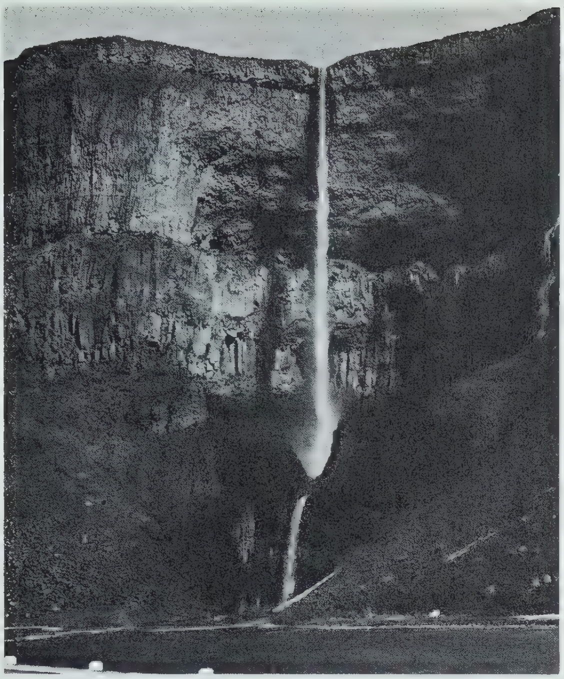
There are volcanic rocks in some of the valleys to the southwest of Philipsburg, Montana, but not in the area shown in Figure 12–2. Farther to the south, however, in southern Idaho and westward into Oregon and Washington there is an extensive lava plateau known as the Columbia Plateau.

Figure 12–10 is a map of the Columbia Plateau and the Cascade Range to the west of it. The plateau covers over 260,000 square kilometers. Some individual flows are only a few meters thick. Others may be as much as 50 or 60 meters thick. The oldest flows in the plateau occurred about 50 million years ago, and the youngest perhaps only a thousand years ago.

The Cascade Range borders the Columbia Plateau on the west and extends southward into California. It consists of broad lava fields that are generally younger than the lavas of the Columbia Plateau. Rising above the lava fields are many spectacular volcanic cones such as Mount Rainier (Figure 12–12), Mount Shasta, and Lassen Peak. Three of these volcanoes have been active in the last two centuries.

Figure 12–10
The blue line marks the boundaries of the Columbia Plateau and the Cascade Range.

a.



b.

FIGURE 12–11

a. *A thick sequence of lava flows on the Columbia Plateau.*

b. *The ropy surface of recent lava flows in Craters of the Moon National Monument, Idaho.*

FIGURE 12–12

Mount Rainier is one of the volcanic cones of the Cascade Range.

12–10
Investigating volcanic rocks

The great bulk of plutonic rocks are granitic. The great bulk of all volcanic rocks are basaltic. They are different from the granitic rocks in mineral composition and in chemical composition, as you will see in this investigation.

Procedure

Examine the specimens of volcanic rocks.

1. *What is the main difference between these rocks and plutonic rocks?*
2. *Assuming that these rocks have about the same chemical composition as plutonic rocks, how would you explain the difference?*
3. *Separate the specimens into two groups: light-colored and dark-colored (dark gray or black). Which group would you consider to be granitic and which basaltic?*
4. *Ask the teacher to provide rock names for the specimens. If you have a piece of obsidian, in which color group did you place it?*
5. *Obsidian is actually granitic. Can you suggest why it is black?*

Figure 12–13 shows the minerals in the two types of igneous rocks. Determine the percentage of each mineral along a vertical line through the middle of the shaded area labeled "granitic." Record the results. Do the same for a line through the middle of the shaded area labeled "basaltic."

6. *What are the main mineral differences between granitic and basaltic rocks?*

Thought and Discussion

1. Nearly all obsidian is geologically young. There are no obsidians among volcanic rocks more than a few million years old. Try to think of at least two possible reasons for this situation.
2. How could you distinguish between a basaltic lava flow covered by a layer of younger sedimentary rock and a layer of basaltic rock injected between two layers of older sedimentary rock?
3. Considering the great volumes of granitic rocks in plutons why are rocks of this composition so rare among the volcanic rocks?

Unsolved Problems

Many of the ideas presented in this chapter are controversial. The sequence of events in the development of a typical mobile belt at the margin of a continent is acceptable to most geologists. This is about as far as agreement goes.

What, for example, is the origin of plutonic rocks? Remember that the granitic plutonic rocks form below the surface, surrounded by metamorphic rocks. We have said that the intensity of metamorphism decreases away from the plutons in all directions. It could also be said that metamorphism increases in intensity toward the plutons. This suggests to some that the plutonic rocks are actually the result of metamorphism! Metamorphism might have been so intense that partial melting occurred and produced a molten mass of rock material.

This could move upward in an active mobile belt and intrude into solid rocks above. Do plutons represent the hot spot in the center of the metamorphic mass?

Another question concerns the relation of plutonic rocks to volcanic rocks. Both plutonic and volcanic rocks appear to have formed from hot, mobile rock material called magma. And both are commonly considered to be varieties of igneous rock. Yet they are different in chemical and mineral composition and form at different times and in different environments. For example, volcanic rocks on and near mountain ranges are much younger than the plutonic rocks in the same area. Why?

The answers to these questions are mostly speculative. It seems clear that the processes involve dynamics affecting the whole earth's crust and probably deeper layers of the earth's interior.

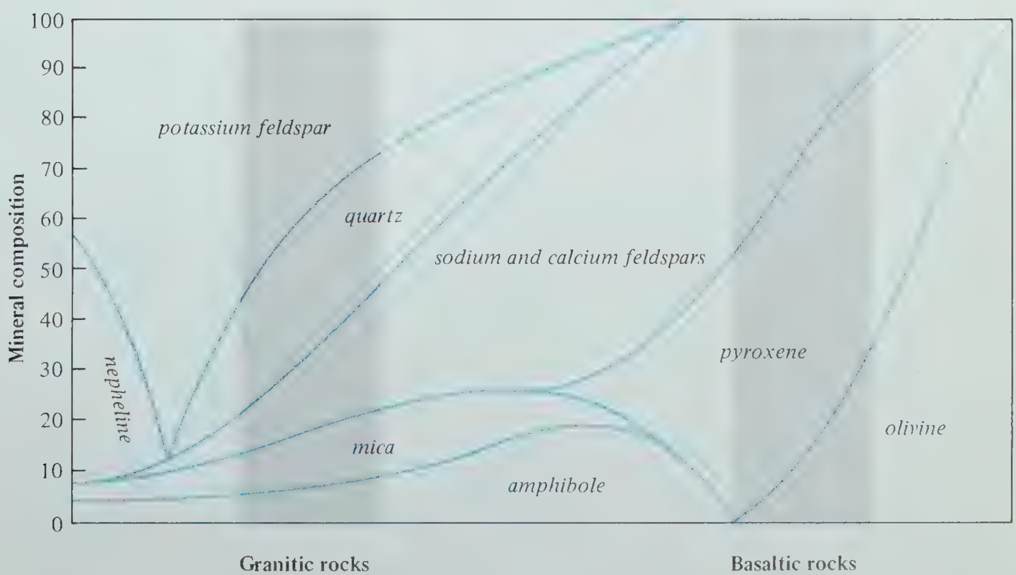
Chapter Review

Summary

The most abundant rocks of the continents form in mobile belts. The continents have grown by the repetition of mobile belts along their margins. It has recently been estimated that 75 per cent of all sedimentary rocks formed during the past three billion years were originally deposited in geosynclines.

Distinctive rocks form within and upon mountain ranges developed in mobile belts. The typical sequence of events is: 1) The deposition of sedimentary rocks during the geosynclinal phase. 2) Deformation, folding, and faulting. 3) Late in the deformation phase but commonly before its completion, the formation of plutons of granitic rock accompanied by metamorphism and the formation of metamor-

Figure 12–13
The characteristic minerals of igneous rocks. Compare the composition of granite and basalt.



phic rocks. 4) Considerable uplift and erosion, producing rugged mountain scenery and in some instances exposing the plutonic and metamorphic rocks. 5) Volcanism, the outpouring of basaltic lava from vents and fissures within the mountain belt. 6) Additional uplift and erosion until the mountain system is destroyed, exposing the deeper levels of plutonic and metamorphic processes. 7) The eroded material is deposited in a new geosyncline. This is the natural rock cycle.

The materials of the earth's upper crust are exposed in the mountains and the roots of former mountains. The upper crust is a relatively thin layer of soil and sedimentary, metamorphic, plutonic, and volcanic rocks.

Metamorphic rocks have formed from preexisting rocks without melting, but at high temperatures and pressures. The degree of metamorphism of a rock reflects the temperature and pressure the rock was subjected to.

Igneous rocks are believed to form from magma. Magma is molten rock material containing small amounts of water vapor and other gases. Igneous rocks can probably originate in at least three ways. Some granitic rocks may have developed from an original basaltic parent magma. Others have crystallized from magma formed during melting of sedimentary rocks. Rocks that appear to be igneous may also form during mountain building by a kind of extreme metamorphism.

The basaltic volcanic rocks obviously form from hot, mobile rock material that reaches the surface. It probably comes from below the crust.

Questions and Problems

A

1. Why are environmental conditions within the crust different from those on the surface of the earth?
2. Why are some igneous rocks fine-grained and some coarse-grained?
3. What is likely to happen to sandy clay sediment buried for a long time at a depth of 20 kilometers? How might such rock be changed into granite?

B

1. Estimate the difference between the approximate temperature when rocks begin to melt and the average crustal temperature at a depth of 20 kilometers. Assume the rock composition is granitic. (Refer to Figures 12–4 and 12–9.) What is the significance of this temperature difference?
2. Are all granites igneous in origin? In what other way do granites form?

C

1. By melting granite in an open container, early investigators tried to discover the lowest temperature at which a magma of this composition could exist. How meaningful were such experiments? What other factors should be controlled to make such experiments more meaningful?
2. Certain ancient rocks exposed in mountains are called volcanic rocks. Since their formation was not seen, how do you think it can be determined that they are volcanic?

3. Suppose that the earth had no atmosphere. Would this have any effect on the amounts and kinds of rocks that compose the crust?
4. What evidence indicates that plutonic and volcanic rocks are not two parts of a single event in a mobile belt?

Suggested Readings

Bayly, Brian, *Introduction to Petrology.* Prentice-Hall Inc., Englewood Cliffs, New Jersey, 1969.

Mather, Kirtley F., *The Earth Beneath Us.* Random House, New York, 1964.

Romey, William D., *Field Guide to Plutonic and Metamorphic Rocks.* ESCP Pamphlet Series, Houghton Mifflin Co., Boston, 1971.

Shelton, John S., *Geology Illustrated.* W. H. Freeman and Co., San Francisco, 1966.

Wyllie, P. J., *The Dynamic Earth.* John Wiley & Sons, Inc., New York, 1971.

13. The Driving Force of the Rock Cycle

So far you have been learning about earth processes on or near the earth's surface. You have seen, for instance, how sediments are deposited and mountains are uplifted and eroded. You have seen that volcanic lava and ash can spread over large parts of the earth's surface and even build up to form mountains.

There was a general belief for many years that the earth was largely a "frozen" planet. Dramatic geological events such as volcanic eruptions and earthquakes were thought to be produced by the small amount of heat left over from the cooling of our once molten planet. There was no idea that surface processes had any common driving force.

Recently, however, we have begun to realize that earth processes do not happen randomly. Volcanic eruptions and earthquakes occur chiefly in definite zones on the earth's surface. California's San Andreas Fault is shown on the opposite page. It is one of the most notorious instances of the crust's response to a central driving force within the earth. The interior of the earth is not frozen, but is a dynamic "machine" that drives the rock cycle.

Studying the Interior of the Earth

13–1
Investigating the inside of a sphere

The hidden interior of an object can be studied without seeing or sampling it. Your teacher will give you two spheres that seem to be the same. But are they? Experiment with them and see. Make whatever observations or measurements you think are necessary and record any similarities and differences that you detect.

13–2
Earthquake waves and the earth's interior

One way that energy travels through matter is in waves. By analyzing how waves travel, we can learn a lot about the contents of a substance and how various parts of it are arranged. In fact, this method is the geologist's most important tool for studying what he cannot actually sample: the inside of the earth.

Imagine that you just dropped a rock in a pond. Watch the waves as they move out from the place where the rock splashed down. The first wave is the highest. As it travels, the height of the wave decreases. The waves that follow the first one tend to be lower. Where did the energy that produced the waves come from? Suppose you drop a smaller rock into the water from the same height. Will the waves be the same size as those that were made by the big rock?

Late in the 19th century it was discovered that some of the energy released by earthquakes takes the form of **seismic waves.** Seismic waves radiate from the focus of an earthquake in all directions through the solid rock, in somewhat the same way that waves radiate from a rock dropped in a pond.

Seismic waves are not very high. Waves that have traveled many kilometers through rock vary from only a few thousandths of a millimeter to a few millimeters high. You can see why sensitive instruments are necessary to record them.

There are different types of seismic waves. One type is a **compressional** or primary (P) wave. When a compressional wave passes through a substance, individual particles move back and forth as shown in Figure 13–1. The action is like the expansion and contraction of a spring, except that P waves travel at thousands of miles an hour. P waves can travel through solids, liquids, and gases.

Another type of wave is a **shear wave** or secondary (S) wave. (See Figure 13–1.) In shear waves the individual particles vibrate from side to side at right angles to the direction the wave is traveling in. A consequence of this is that S waves cannot travel through liquids.

By studying waves that traveled deeply into the earth, scientists have discovered that the earth has a core of very dense material (Figure 13–2). The inner part of the core is solid. Because S waves do not pass through the outer part of the core, geophysicists reason that it is liquid or behaves like a liquid.

FIGURE 13–1
Particles of matter vibrate as a wave passes. Imagine the particles are equally spaced (top). A compressional wave squeezes and stretches the material (center). A shear wave causes layers of particles to slide past one another (bottom).

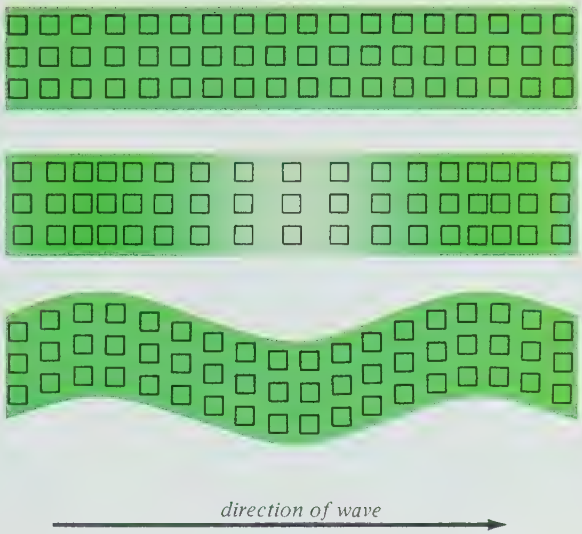
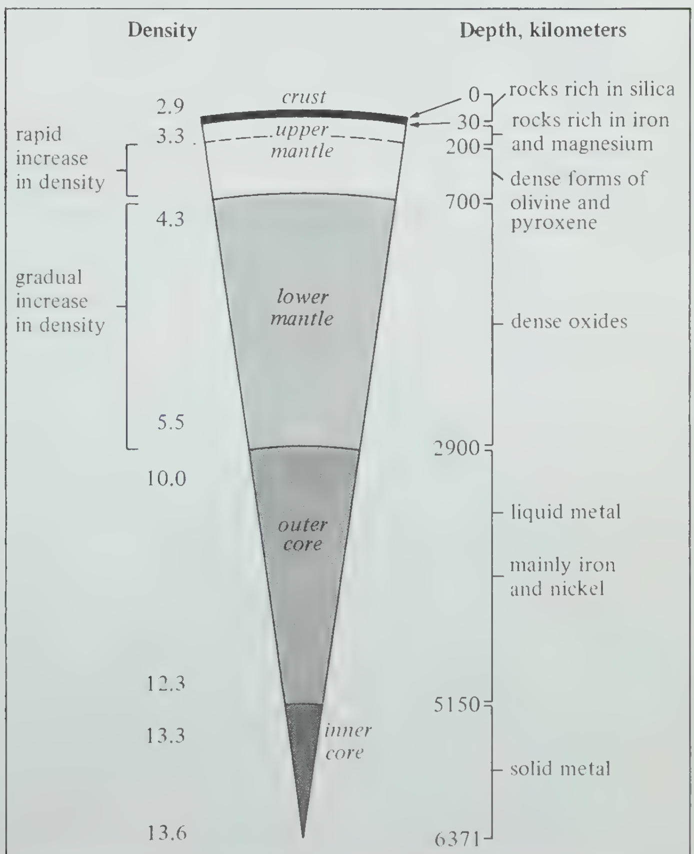


FIGURE 13–2
The layers of the earth.



13–3
The Moho

Geophysicists have determined the thickness of the crust by using a method discovered in 1909 by a Yugoslav seismologist Andrija Mohorovicic, (Moh-hoh-ROH-vih-chich). While analyzing seismograph records of earthquakes, he noticed that at a certain level in the earth there was an abrupt change in the speed at which earthquake waves traveled. This level is now taken as the boundary between the crust and **mantle.** The mantle is the region between the crust and the core. (See Figure 13–2.) The boundary is called the **Mohorovicic discontinuity**, commonly shortened to the **Moho.** (It should not be confused with the Mohole, the drill hole which was planned to penetrate the Moho but was never finished.)

The change in the speed of seismic waves is apparently caused by density differences between rocks of the crust and the mantle. Geophysicists are now using seismographic records made all over the world, both on land and sea, to establish the depth of the Moho. This crust-mantle boundary zone averages about 10 kilometers below sea level in ocean basins and about 30 kilometers beneath high mountains.

FIGURE 13–3
Arrival Times of Washington, D.C., Earthquake Waves

CITY	DISTANCE IN KILOMETERS	P WAVE ARRIVAL TIME (G.M.T.)	S WAVE ARRIVAL TIME (G.M.T.)
BUENOS AIRES, ARGENTINA	8640	8:11:50	8:21:42
CAIRO, EGYPT	9590	8:12:37	8:23:12
BOGOTA, COLOMBIA	4840	8:08:05	8:14:25
CHICAGO, ILLINOIS	988	8:01:54	8:03:32
LONDON, ENGLAND	6060	8:09:27	8:17:06
LOS ANGELES, CALIFORNIA	3810	8:06:42	8:12:11
MEXICO CITY, MEXICO	3120	8:05:48	8:10:32
HOUSTON, TEXAS	2010	8:04:08	8:07:28
MOSCOW, U.S.S.R.	8040	8:11:20	8:20:41
NEW YORK, NEW YORK	339	8:00:38	8:01:18
SAN FRANCISCO, CALIFORNIA	4040	8:07:00	8:12:40
STOCKHOLM, SWEDEN	6800	8:10:12	8:18:31

Seismic investigations are carried out not only by monitoring earthquakes but also by setting off an underground explosion on one side of some mountains. The waves radiating outward to the other side of the mountains are measured. Seismic waves travel at different speeds in different kinds of rock. Therefore, from measured wave speed, something can be learned about the nature of the rock and the thickness of the layers. By moving the sites of the explosion and detectors farther and farther apart, waves that travel deeper in the earth can be detected.

The earth's mantle is denser than the crust. Seismic evidence has shown that the mantle probably consists mostly of olivine-pyroxene rich rocks and garnet-pyroxene rich rocks. There is also evidence that the core is mostly iron with a small amount of nickel.

13–4 Locating the epicenter of an earthquake

One of the most important tools of a seismologist is a travel-time graph. It is used to locate the epicenter of an earthquake, the point on the earth's surface that is directly above the focus of the earthquake. You will make a travel-time graph in this investigation.

The P and S waves from an earthquake travel at different velocities from the focus through the earth. As a result, although they both originate at precisely the same time and place, they arrive at distant seismograph stations at different times.

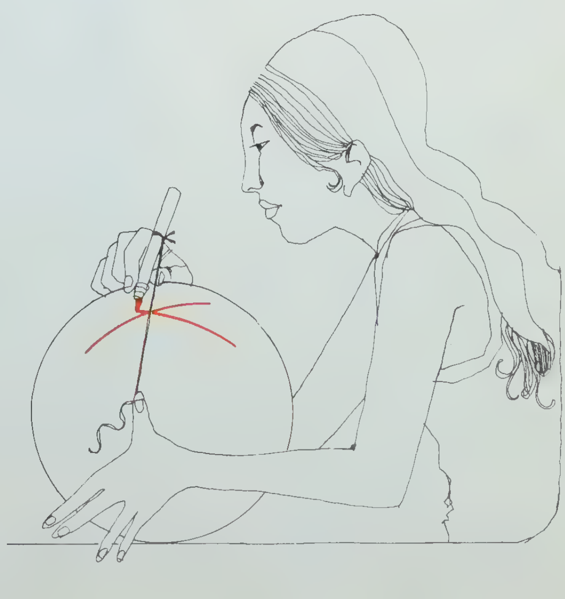
Procedure

Suppose that a mild earthquake was recorded by a seismograph near Washington, D.C. at 08:00:00 Greenwich Mean Time (the time in Greenwich, England). The shock was registered on seismograms in different cities at the times shown in Figure 13–3.

Plot a graph showing travel-time versus distance for both the P and S waves. Once you have constructed the travel-time graph, use it to answer the following questions:

1. *How long does it take for a P wave to travel from the focus of an earthquake to a seismograph station 2,000 kilometers away?*
2. *How long does it take for an S wave to travel the same distance?*
3. *What is the difference in arrival time between P and S waves for an earthquake that is 3,000 kilometers away from the station? 5,000 kilometers from the station?*

Draw arcs the correct distance from each seismograph station and find where they intersect.



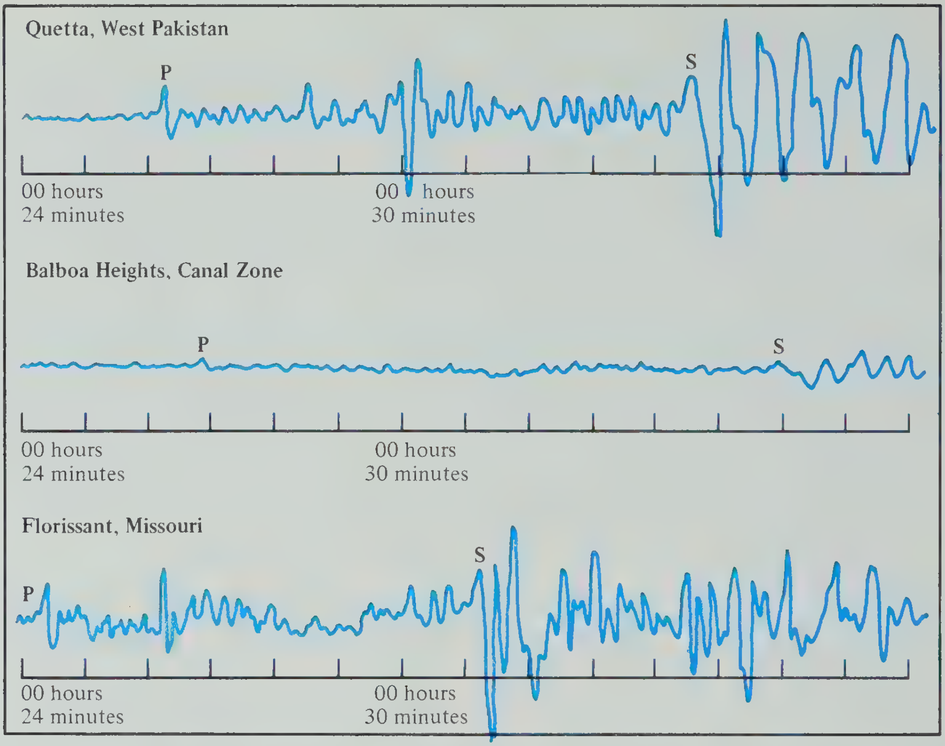


Figure 13–4
Find the epicenter of the earthquake that produced these three seismograms.

Figure 13–5
This winery lies on the San Andreas Fault.

4. *How is the distance of a seismograph station from the earthquake related to the arrival time of the waves?*

Using your travel-time graph and a globe try to locate the epicenter of the earthquake that produced the energy shown on the seismogram tracings in Figure 13–4. The numbers you are using are taken from actual seismograms. Time marks appear on each of the seismograms to provide common reference points.

13–5 Earthquakes and the rock cycle

Earthquakes not only help lift mountains, they also influence the entire rock cycle. For example, the Alaskan earthquake of 1964 triggered large-scale land spreading, landsliding, and submarine slides. Earthquakes are awesome evidence that some process is at work below the surface of the earth. Large masses of magma may be in motion. These movements can result in a sudden release of energy by fracturing the overlying, brittle rocks.

During earthquakes, rocks beneath the surface are clearly bent and broken. In other cases deformation takes place slowly and without recognizable earthquake shocks. For example, in a drill hole in the Great Valley of California, earth movements have been measured for years. Thrusting is going on there at a rate of four feet per century.

Another example of slow earth movements is taking place at a winery in Hollister, California. By chance it was built exactly on the San Andreas Fault Zone. Over the years, there have been slow, steady movements without accompanying earthquakes. The winery building, originally a rectangle, has been pulled into a diamond shape (Figure 13–5). The land at this particular location moves one centimeter a year.

In other places, when rocks break and slip rapidly, there is a sudden release of energy that has accumulated in the rocks for many years. This produces an earthquake. Most earthquakes are so small that they can be detected only by sensitive instruments. When they are violent and occur in inhabited areas, they cause great destruction and misery.

ACTION *To relate earthquake vibrations to those which are more familiar to you, try to analyze what happens when you use a rubber band to shoot a paper wad across the room.*

The wad has kinetic energy as it is propelled from you. Does the amount of energy released change if you stretch the band quickly or hold it stretched a long time before you release the wad?

The vibrations you feel when the wad is released, or when the band breaks, are similar to the vibrations that are set off when something breaks in the earth.

In large earthquakes most of the stored energy is released in the first slippage along the fault surface. However, energy continues to trickle off in **aftershocks,** quakes of lesser magnitude than the main shock. These may continue for months after the initial earthquake.

13–6
Earthquake intensities

At 5:30 in the afternoon of Good Friday, March 27, 1964 many people at Anchorage, Alaska were busy doing their last minute shopping for Easter Sunday. The scene was peaceful and normal. Suddenly at 5:36 the earth began to shake. One woman waiting in her car for a traffic light to change, found herself and her car bouncing sideways across the street. Buildings were rocked so violently that the people inside fell down. Some buildings were only slightly damaged. Some fell apart. Others might have withstood the shaking, but the ground gave way beneath them. Lights went out all over the city.

Seismic waves caused destruction as far as 175 kilometers from the source of the shock in Prince William Sound, about 150 kilometers east of Anchorage (Figure 13–6). Vertical displacement of the earth's surface was as great as 12 meters on Montague Island. The earthquake set off seismic sea waves (tsunamis) in the ocean, which were recorded thousands of kilometers away and wiped out docks and buildings along shorelines near Valdez.

A gravity survey had been made around Prince William Sound before the Good Friday earthquake. Following this quake, the area was resurveyed. It was learned that the values had changed. Apparently, the up and down movements of the land were also accompanied by movements of materials below the surface, which caused observable variations in gravity.

People are interested in the amount of property damage and the number of lives lost in earthquakes. These figures tell us what has happened to people in an earthquake area, but do not give us an accurate idea of what went on inside the earth. For example, in the Agadir, Morocco earthquake of February 29, 1960, at least 12,000 people were killed. The property damage was many millions of dollars. In the Good Friday earthquake 115 people were killed, and property damage was probably not much greater than in Morocco. Yet the total energy released in the Good Friday earthquake was at least 6,000 times greater than the Agadir earthquake. The 1971 San Fernando, California earthquake was only "moderate," but the damage was great because it took place in a highly populated area.

The first **intensity scale** for measuring earthquakes (Figure 13–7) was developed more than

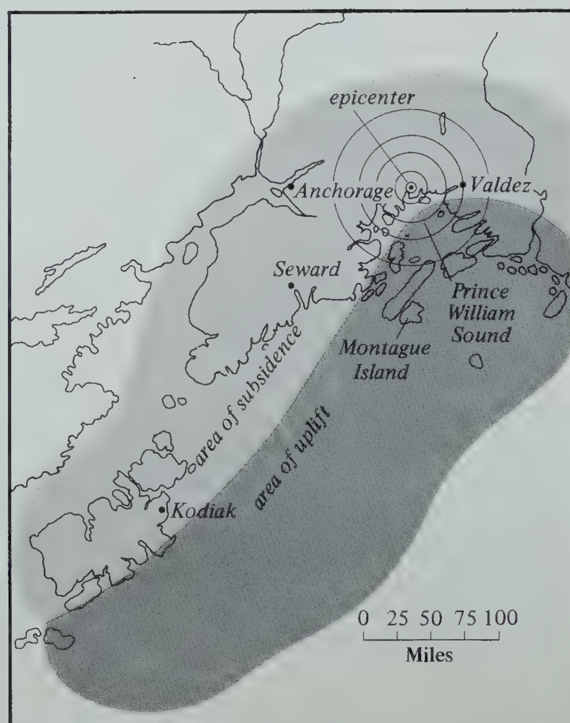


FIGURE 13–6
The epicenter of the 1964 Alaskan earthquake was midway between Anchorage and Valdez.

Figure 13–7
Modified Mercalli Scale of Earthquake Intensity

1. Not felt except by a very few under especially favorable circumstances. Birds and animals uneasy. Delicately suspended objects may swing.
2. Felt only by a few persons at rest, especially on upper floors of buildings.
3. Felt noticeably indoors, especially on upper floors of buildings, but many people do not recognize it as an earthquake. Parked cars may rock slightly. Vibrations like the passing of light trucks. Duration of shaking can be estimated.
4. Felt indoors by many, outdoors by few. If at night, some awakened. Dishes, windows, doors disturbed. Walls creak. Sensation like the passing of heavy trucks. Parked cars rock noticeably.
5. Felt by nearly everyone. Some dishes, windows, etc. broken. A few instances of cracked plaster. Unstable objects overturned. Disturbances of trees, poles and other tall objects sometimes noticed. Pendulum clocks may stop.
6. Felt by all. Many frightened and run outdoors. Some heavy furniture moved. Books knocked off shelves, pictures off walls. Small church and school bells ring. A few instances of fallen plaster or damaged chimneys. Otherwise damage is slight.
7. Everybody runs outdoors. Difficult to stand up. Negligible damage in buildings of good design and construction; slight to moderate in well-built ordinary structures; considerable in poorly built or badly designed structures; some chimneys broken. Noticed by persons driving cars.
8. Damage slight in specially designed structures; partial collapse in ordinary buildings; great damage to poorly built structures. Panel walls thrown out of frame structures. Chimneys, factory stacks, columns, monuments, and walls fall. Heavy furniture overturned. Small amounts of sand and mud ejected from cracks in the ground. Changes in well water.
9. Damage considerable in specially designed structures; well-designed frame structures thrown out of plum; partial collapse of substantial buildings. Buildings shifted off foundations, ground cracked. Serious damage to reservoirs and underground pipes. General panic.
10. Some well-built wooden structures destroyed; most masonry and frame structures destroyed. Ground badly cracked. Rails bent slightly. Considerable landslides from river banks and steep slopes. Shifted sand and mud. Water splashed over banks.
11. Few masonry structures remain standing. Bridges destroyed. Broad fissures in ground. Underground pipelines out of service. Earth slumps and land slips in soft ground. Rails bent severely.
12. Damage total. Waves seen on ground surfaces. Lines of sight and level distorted. Objects thrown upward into the air.

100 years ago by the Italian seismologist, Mercalli. He developed his scale before there were any satisfactory earthquake recording instruments.

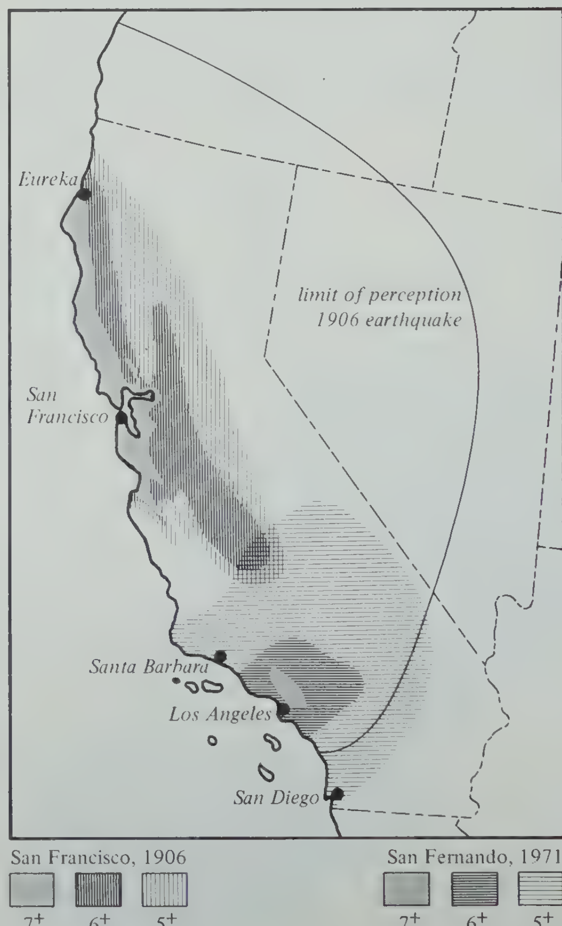
The Mercalli Scale gives a rough indication of the amount of shaking the earthquake caused at a specific place as observed by man. Intensity numbers for many places are determined for each earthquake. The maximum intensity for the earthquake region may be given as *the* intensity of the earthquake. Figure 13–8 shows the distribution of intensities for the 1906 San Francisco and the 1971 San Fernando earthquakes.

C. F. Richter, an American seismologist, developed another method for measuring earthquakes. He assigned a number to each earthquake according to its magnitude, the amount of energy released at the quake's focus. The magnitude is calculated from seismograph records. The Richter Scale (Figure 13–9) therefore describes an earthquake independently of its effects on man and civilization. There is only one number for each earthquake. It was possible, knowing the amount of energy to be released in a deep underground nuclear blast at Amchitka, Alaska on November 5, 1971 to predict that the vibrations would have a value on the Richter Scale near 7.

Thought and Discussion

1. If a seismic wave travels faster in olivine than it does in quartz, what does this tell you about the density of olivine?
2. Why do scientists think the earth's inner core is mostly iron?
3. Where do you think scientists should start to drill if they want to reach the Moho in the shortest distance?
4. If you were building a house near the San Andreas fault zone, what are some of the things you could do to make the house "earthquake proof"?
5. Do you think people should live in active earthquake zones?

FIGURE 13–8
The intensities of two California earthquakes. Which one was bigger?



The Rock Cycle's "Machine"

13–7
The earth's nuclear powered heat engine

In the 19th century Lord Kelvin, a famous physicist, tried to calculate the earth's age. He concluded that it was 20 to 40 million years old. His calculations were based on the cooling and crystallization rates of an originally molten earth. Kelvin assumed that the earth has no internal source of energy. Any energy or heat that is possessed had to be chiefly left over from the originally molten earth, with the exception of those small amounts added by the sun.

Kelvin's calculations were correct, but his basic assumption was wrong. He did not know about minerals containing radioactive heat sources. Radioactive isotopes of uranium, thorium, and potassium are present in some kinds of rocks. Much of what we now know about radioactivity and the distribution of radioactive heat sources was a result of intensive research since 1935 on nuclear devices.

Figure 13–9
Richter Scale of Earthquake Magnitude

Magnitude	Equivalent Energy by Mass of TNT[a]	Remarks
0	600 grams	enough to blast a stump
1	20 kilograms	small construction blast
2	600 kilograms	average quarry blast
3	20 tons (metric)[b]	large quarry blast
4	600 tons	small atom bomb
5	20 kilotons[c]	"standard" atom bomb
6	600 kilotons	small H bomb
7	20 megatons[d]	enough energy to heat N.Y.C. for one year
8	600 megatons	enough energy to heat N.Y.C. for 30 years
9	20,000 megatons	the energy in the world's production of coal and oil for five years.

[a] All numbers are rounded off.
[b] the U.S. ton = 0.9 metric tons.
[c] 1 kiloton = 1000 metric tons.
[d] 1 megaton = 1000 kilotons.

13–8 Taking the earth's temperature

Field studies have shown how rocks rich in radioactive heat sources are distributed. Figure 13–10 indicates that granitic rocks contain far greater amounts of radioactive isotopes than basaltic rocks. Basaltic rocks in turn have a far higher radioactive content than either mantle rocks or meteorites. The several radioactive isotopes in granitic rocks produce nearly five times as much heat as the isotopes in basaltic rocks. And the basalts in turn produce almost 40 times as much heat as mantle rocks or meteorites.

The heat we feel at the surface of the earth, unless we are near an erupting volcano or a hot spring, is chiefly from the sun. However, the earth produces great amounts of heat in its interior. The latest calculations indicate that 30–40 calories per square centimeter reach the surface of the earth each year from the decay

FIGURE 13–10
Radioactive Content and Heat Release for Various Terrestrial Rocks

	Uranium *parts per million*	Thorium *parts per million*	Potassium ^{40}K *parts per million*	Heat Production *Microwatts per cubic meter*
A. *Crustal Rocks*				
GRANITIC IGNEOUS ROCKS	4.0	16.0	402.0	2.5
BASALTIC IGNEOUS ROCKS	0.5	1.5	61.0	0.3
SHALES	4.0	12.0	330.0	2.1
LIMESTONES	2.2	1.7	37.0	0.7
BEACH SANDS	3.0	6.0	37.0	1.2
B. *Possible Mantle Rocks*				
DUNITE	0.005	0.02	0.12	0.004
ECLOGITE	0.04	0.15	12.0	0.04
PERIDOTITE	0.022	0.066	2.70	0.01
C. *Rocks Possibly Similar to Core Rocks*				
IRON METEORITE	0.00011	?	?	0.00006

of radioactive elements. This is enough to melt a world encircling layer of ice about one centimeter thick.

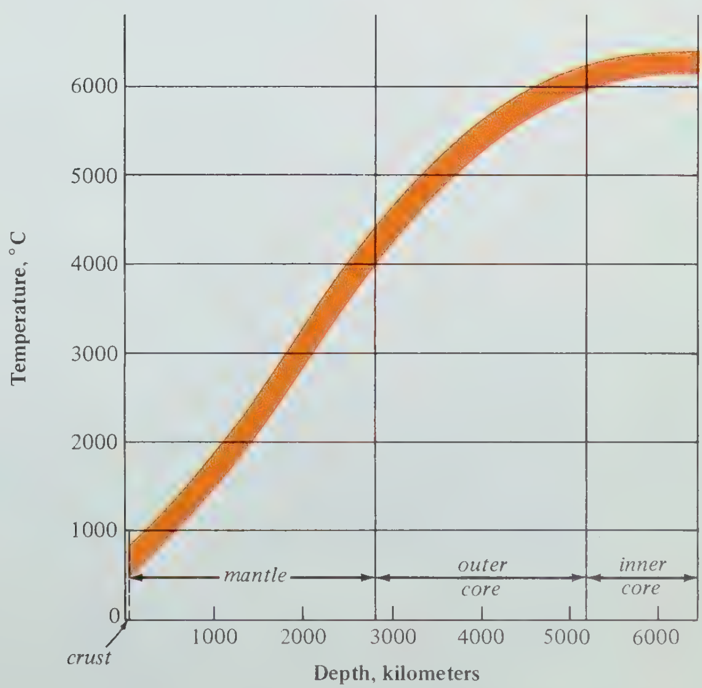
The speed with which heat generated inside the earth flows to the surface and escapes depends on the conductivity of the rock. Rock is such a poor conductor that, for the most part, heat now reaching the surface of the earth has probably taken all of geological time to travel from a maximum depth of several hundred kilometers.

It takes sensitive instruments to measure directly the surface heat flow which comes from the interior of the earth. The temperature of sediments in water below a few hundred feet is stable. Therefore, direct measurements of heat flow in the oceans are now readily made. On the continents a number of precautions must be taken in measuring heat flow in rocks near the surface. Seasonal changes in temperature and the movement of ground water of varying temperatures can affect the results. Thus, subsurface temperatures are best measured in drill holes, mine shafts, tunnels, and oil wells, which reach below the zone of surface variability.

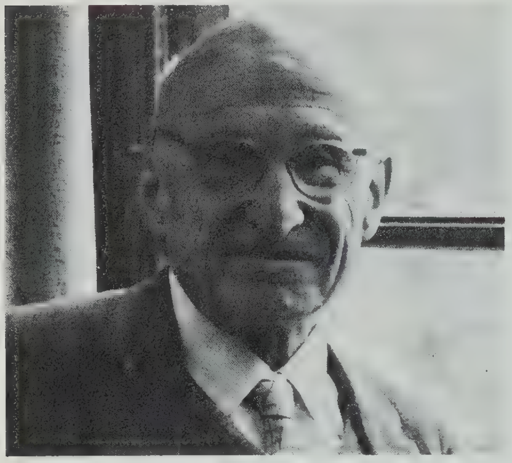
Heat flow is measured in drill holes and mines by instruments called thermistors. They show that the earth's temperature in any locality, volcanic or not, increases with depth. The rate of temperature increase is called the **geothermal gradient** (Figure 13–11). In nonvolcanic areas this gradient averages 30°C per kilometer of depth or about 1°C per 30 meters. However, since scientists have been able to drill only a little over nine kilometers into the earth's crust, any information on heat flow below this depth must be inferred from indirect evidence.

If the geothermal gradient continued at the same rate to greater depths, the temperature

Figure 13–11
Estimated temperatures in the earth's interior.



BENO GUTENBERG



Beno Gutenberg (1889–1960) became interested in studying the earth's internal structure at the University of Gottingen, Germany. He eventually became a world authority on how earthquake waves travel through the earth. In 1914 he located the boundary of the earth's core at 2,900 kilometers below the surface. From this determination he found the thickness of the mantle. He also claimed there was a central or inner core 3,470 kilometers below the earth's surface.

From his extensive studies of the earth's interior, Gutenberg became convinced that major geologic changes were caused by the spreading of continents. He believed that the continents were gradually growing as material came up from deep within the earth through rifts in the sea bottom. Gutenberg thought that this process of growth caused the continents to move. Later discoveries of mid-ocean ridges supported his ideas.

Gutenberg compiled his lifelong research into a book entitled *Physics of the Earth's Interior*, which was published in 1959, the year before he died. It has since become a standard reference for geophysicists throughout the world.

at the earth's center would have to be about 200,000°C. Much of the interior of the earth would be molten. But we know from earthquake studies that the only large part of the earth's interior that is molten is the outer core from about 2,900 to 5,100 kilometers.

13–9
Heat flow provinces

Within the continents and oceans a number of **heat flow provinces** have been mapped. Their boundaries are commonly at geographical landforms. Ocean ridges, for example, are characteristically provinces of high, but variable heat flow. Ocean basins are typically of moderate, relatively uniform flow. The trenches are low heat flow provinces. Why is heat flow so variable over the earth's surface? Many scientists believe that giant convection currents operating within the earth may explain this phenomenon.

ACTION *Fill a beaker with water and sprinkle some sawdust on the surface. Heat the water and observe the movement of the sawdust.*

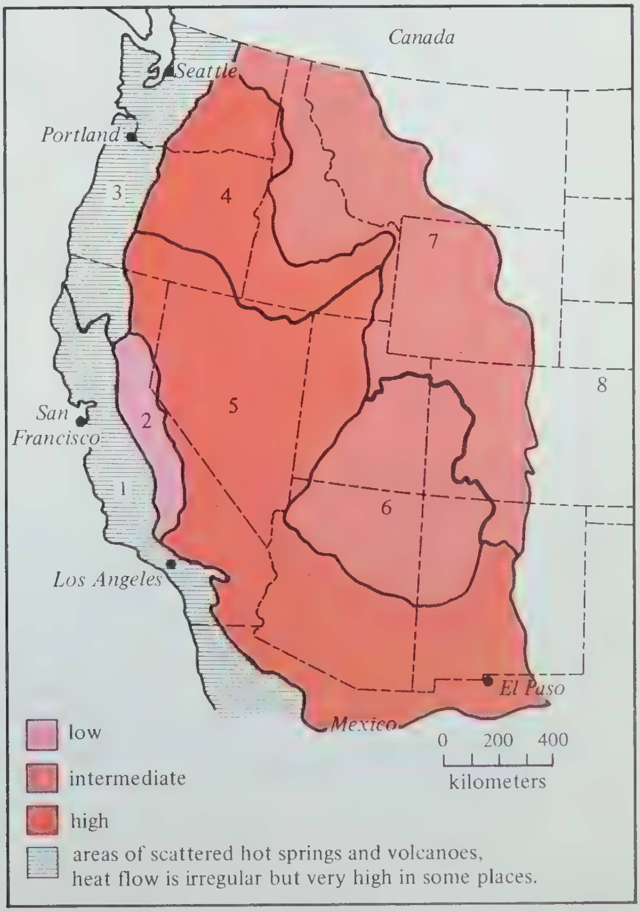
Heating the water caused convection currents. You could observe the movement of these currents by watching the path of the sawdust. Since we know that the interior of the earth is heated by radioactivity, perhaps similar convection currents could be operating within the earth. Remember that even the most rigid substance will respond by flowing if stress is applied over long periods of time. Thus, the earth's mantle could be flowing in convective patterns in response to radioactive heating throughout geologic time.

The surface expression of an upwelling current would be the mid-ocean ridges. They are characterized by high heat flow values, volcanic activity, and a spreading apart of the earth's crust.

Two convective cells can merge in a low heat flow area where the crust has cooled since being extruded at the mid-ocean ridges. At such a place the crust is squeezed together, and part is dragged down into the mantle. Much folding and faulting occurs.

The old nuclei of continents, the Precambrian shields, have low heat flow values. On the other hand, regions of much younger mountain building activity have variable high and low heat flows. The Basin and Range and the Sierra Nevada Provinces (Figure 13–12) are good examples.

FIGURE 13–12
Heat flow provinces in the western United States: 1) and 3) coastal provinces, 2) Sierra Nevada, 4) Columbia Plateau, 5) Basin and Range, 6) Colorado Plateau, 7) Rockies, and 8) stable interior.



Observed heat flow values generally support the theories of seafloor spreading and plate tectonics. Heat flow is high along ridges where hot material is thought to be rising. In contrast, heat flow is found to be low near trenches, where a cold plate is thought to be descending.

Magnetic evidence also supports the theory that sea floor spreading is caused by convection cells in the mantle. Scientists have evidence that the earth's magnetic field has reversed itself periodically through geologic time. (See Figure 13–13.) Suppose the mantle flows in convective patterns, causing the sea floor to spread. The magnetic reversals would be recorded in "stripes" paralleling the mid-ocean ridges. The reason is that when molten rock cools, any magnetic minerals are magnetized in the direction of the magnetic field existing at that time. These "stripes" have been observed in rocks taken from the Mid-Atlantic Ridge near Iceland. They are further evidence for the existence of convective motion within the mantle. (See Figure 13–14.)

Using the latest heat flow data, scientists have set up models of tectonic movements on computers. Figure 13–15 shows the results of one computer study. It is a cross section of the outer 900 kilometers of the earth showing a descending slab 80 kilometers thick composed of oceanic crust and upper mantle. The slab has been descending at the rate of one centimeter per year, for about 100 million years. The diagram takes into account radioactive heating and heating caused by friction as the slab slides into the mantle.

Thought and Discussion

1. How can solid rock flow?
2. How do magnetic studies support the theory of plate tectonics?
3. What is one major source of the earth's interior heat?
4. If convection cells are operating within the earth, and they suddenly reversed direction, what effect do you think this would have on the earth's surface?

Unsolved Problems

In trying to understand the rock cycle within the earth, scientists have been able to answer many difficult questions. Yet many problems remain unsolved. Research on predicting earthquakes has been given top priority, especially since the 1964 Alaska and 1971 San Fernando quakes. Scientists want to provide communities that lie in earthquake zones with an early warning service. People living in those areas could then be evacuated in time to prevent loss of life.

Scientists use instruments to measure stresses acting on rocks in certain areas. If the magnitude of these stresses changes suddenly, an earthquake may be about to occur. They have also noted that clusters of small magnitude quakes tend to occur a few hours before a large earthquake hits an area.

With this data, scientists may be able to predict a major earthquake a few hours before it happens. However, the warning signals mentioned may not occur before all earthquakes.

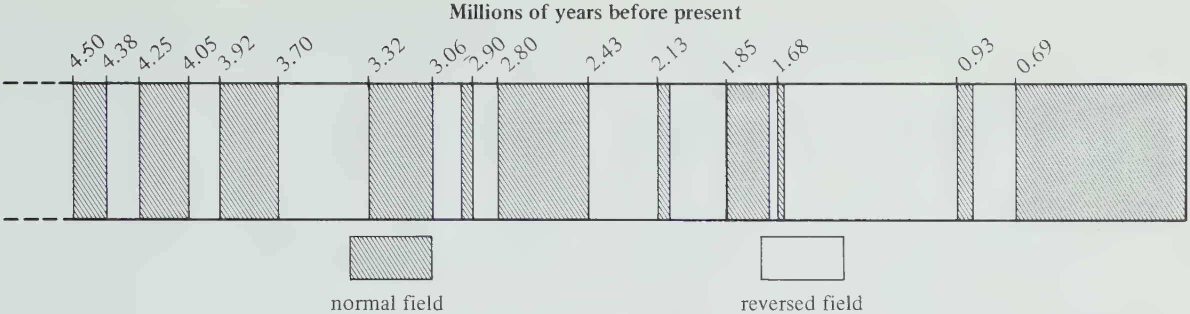


Figure 13–13
(top) Reversals in the earth's magnetic field. How would you define a normal magnetic field?

Figure 13–14
Magnetic "stripes" near Reykjanes Ridge in Iceland. The dark areas represent rocks magnetized in a "normal" direction. The light areas represent rocks of reverse magnetization.

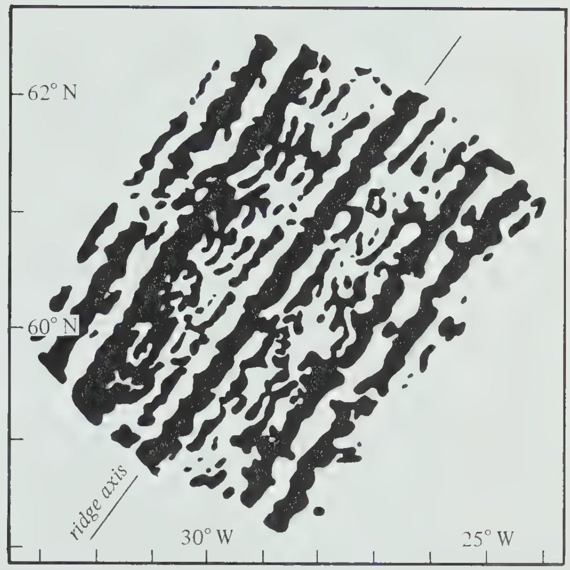
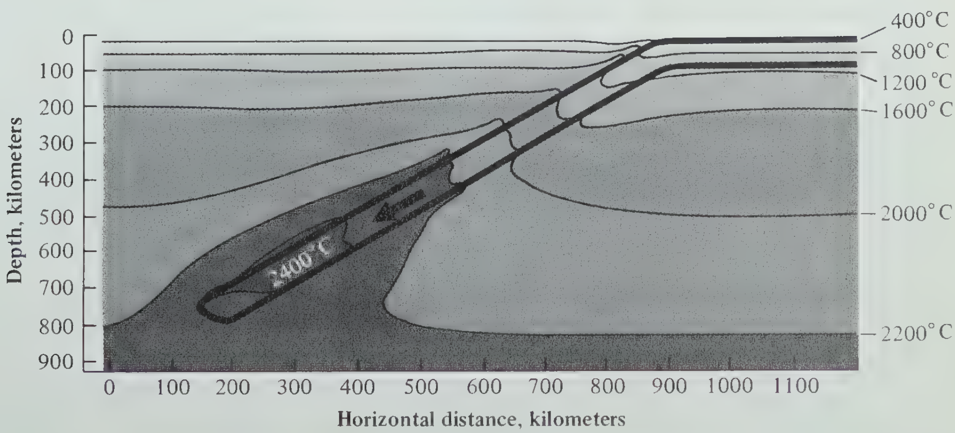


Figure 13–15
A model of the temperatures near a slab of crust descending into the mantle.



Also, even a few hours warning is not enough to insure the safety of the people living in the quake area. Clearly, more work is needed if scientists are to solve the earthquake prediction problem.

Chapter Review

Summary

In this chapter you have learned that the earth's dynamic interior is responsible for movements that occur on the surface. The earth's heat engine—the driving force of the rock cycle—is powered basically by radioactive fuel.

By studying the geothermal gradient, scientists have been able to estimate the temperature in the earth's interior. The amount of heat which flows from the center of the earth to the surface varies, maybe due to convection cells in the mantle. The earth can be divided into provinces according to the amount of heat flow.

Earthquakes are also an expression of the earth's dynamic interior. By studying arrival times of P and S waves, scientists can learn indirectly about the earth's interior. The earth's mass can also be calculated indirectly. Scientists have learned, too, that through time the earth's surface changes in response to forces within the earth. Solids may bend and flow; mountains may be lifted.

Magnetic studies also give evidence of our dynamic earth by supporting newly developed theories of plate tectonics and sea-floor spreading.

Questions and Problems

A

1. What is the major source of heat in the earth's interior?
2. What type of rock has the greatest amount of radioactive isotopes?
3. If the continental rocks contain a larger amount of radioactive materials, how can the heat flow from the oceans and from the continents be approximately equal?
4. What methods can be used to measure the earth's temperature directly?
5. What explanation is given for the fact that S waves do not pass through the earth's core?
6. Why is it easier to measure heat flow in the ocean basins than on the continents?
7. What is the geothermal gradient?
8. Name some areas on the earth's surface where you might expect heat flow to be high.
9. Why can a compressional wave travel through liquids?

B

1. What is the difference between compressional and shear waves?
2. What single fact would you have to know to determine the distance to the epicenter of an earthquake with a travel-time graph?
3. How many seismograph stations must record arrival times so that an epicenter location can be determined?
4. Assuming no erosion, how many earthquakes exactly like the Anchorage earthquake would it take to raise mountains from sea level to heights of the modern day Alps or Himalayas?

5. At the time of the Good Friday earthquake, there was a meeting of the Seismological Society of America in Seattle. Most of the seismologists did not actually feel the earthquake. A number who were having dinner in the restaurant at the top of the Space Needle did feel it. What would be the Mercalli Intensity rating in Seattle?
6. What is the difference between the Mercalli Scale of Earthquake Intensity and the Richter Scale?
7. Can parts of the earth's surface move relative to one another even though an earthquake does not occur? Give an example.

C

1. What evidence can you cite to answer the question of whether the earth's interior is liquid or solid?
2. The radius of the earth is 6,370 kilometers. The location of the core-mantle interface is at a depth of 2,900 kilometers. What percentage of the earth's volume is occupied by the core? What percentage is occupied by the mantle? (Neglect the volume of the crust.)
3. Explain how magnetic evidence supports the theory of sea-floor spreading.

Suggested Readings

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14. Evolution of Landscapes

Some years ago nearly every student had a small plastic ruler which bore this message: "Study nature, not books." This is an excellent motto for anyone who would understand landscapes.

While you study this chapter, observe your local landscape. Keep a written record of your observations. If there are hills and valleys, describe their size, shape, and arrangement. Try to find maps that show details of the local landforms. If there are exposures of rock in road cuts, quarries, or parks, try to identify the kinds of rock. You may not be able to see much of a natural landscape where you live if it's covered with buildings and highways. In that case, take field trips into the countryside.

The casual observer of the landscape sees only scenery, the informed observer reads the storybook of change. The landscape on the opposite page can be admired simply for its sculptured shape. It can also be read as a single, beautiful episode in an endless tale of deposition, uplift, and erosion.

Landscapes in Perspective

14–1
Growth versus breakdown

Basically, three factors determine the shape of the land. The first is *the kind of rock* at the earth's surface and how well it resists weathering and erosion. It makes a difference, for example, whether the bedrock is a uniform mass of granite, horizontal layers of sedimentary rocks, or folded sedimentary rocks.

The second factor is *the movement of the earth's crust*. This includes uplift, subsidence, tilting, bending, breaking, and volcanic eruptions. As we have seen, these processes unlevel the land.

The third factor is a group of *external processes* including weathering, downslope movements such as creep, and erosion. These processes are powered by gravity and energy from the sun. They tend to level the land.

In some places the tug-of-war between uplifting and downcutting can be studied in detail. For example, in Figure 14–1 you are looking northward across a low ridge. It descends gently to the east (right). The land drains toward the north (the top of the picture). Most of the stream channels join to flow through the

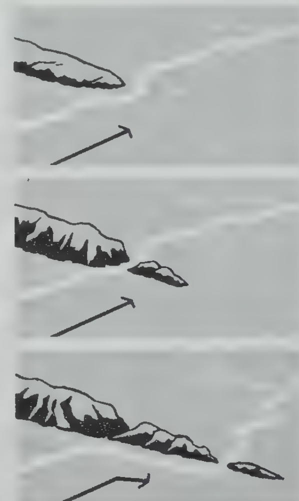


FIGURE 14–1
Wheeler Ridge, California is slowly rising above the surrounding plain. The diagrams show how the rising ridge affects the major stream in the area.

lowest notch in the ridge. The large notch to the west is now merely a pass. Both of these notches have been cut by streams flowing north. Why has the stream ceased to flow through the larger notch?

Examine the ridge more closely. The two notches divide the ridge into three parts. Notice that the western part is cut by many large gullies, but the central part has only a few smaller gullies on its slopes. The low eastern part at the far right has no gullies at all.

The most likely explanation for these contrasting conditions is that the western part of the ridge was uplifted first and has been eroding the longest. The parts toward the east were uplifted more recently. These events occurred during the past one or two million years. If the ridge keeps rising, all the drainage may be forced eastward once again. The streams would cross the ridge through a new channel farther to the east.

FIGURE 14–2
Sheep Mountain, Wyoming. How does this ridge compare to the one in Figure 14–1?

Now look at Figure 14–2. This is another **anticline**, an upward fold of sedimentary rocks. A stream crosses it in a narrow canyon. In contrast to Wheeler Ridge, the canyon is near the widest and highest part of the ridge.

Sometime after the folding which produced the anticline at Sheep Mountain, the area was eroded and then buried under a thick deposit of sedimentary rocks. A river developed on the surface of these younger rocks and eroded its valley. Eventually the river cut down to the older folded rocks. Continued erosion by this river cut the canyon, and erosion by smaller tributaries left the anticline standing in sharp relief above its surroundings.

At Wheeler Ridge each successive stream channel across the anticline is older than the uplift of that part of the ridge. Does the anticlinal nature of Wheeler Ridge suggest a good reason for the abandonment of the oldest notch? At Sheep Mountain the ridge was formed by the erosion of less resistant rocks surrounding it, rather than by uplift.

Crustal movements have been accurately measured many times over the years. Near Cajon Pass in California measurements begun in 1906 show that the land is being uplifted by nearly one centimeter a year.

The Serapeo at Naples, Italy, displays evidence of both subsidence and uplift since Roman times. The average movement here has

also been about one centimeter a year. (See Figure 14–3.)

The anticline in Figure 14–4 has been rising at a slower rate. You can compute the rate from the information in the caption. By comparison with volcanic activity, these rates are all slow. A single volcanic outpouring can add several meters of lava.

14–2
Investigating maps as models

We ordinarily view our world from near the earth's surface. But there are many other ways to view the world. In this investigation you will examine several models of the same subject. Each model has a different point of view.

Procedure

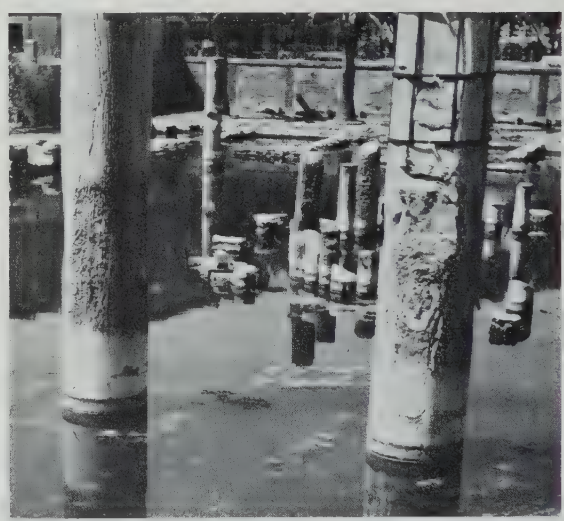
If you were standing in a field near the town of Morrison, Colorado looking north towards Red Rocks Park, you might see the view in Figure 14–5.

1. *If you were asked to make a model of the earth's surface as seen in Figure 14–5, how would you do it?*
2. *What other information would you need to complete your model?*
3. *What additional information does Figure 14–6 provide you with? It is an aerial view of about the same area shown in Figure 14–5.*

Examine the topographic map in Figure 14–7.

4. *How does a topographic map show hills and valleys?*

To better understand the way topographic maps work, you need a transparent box, a model



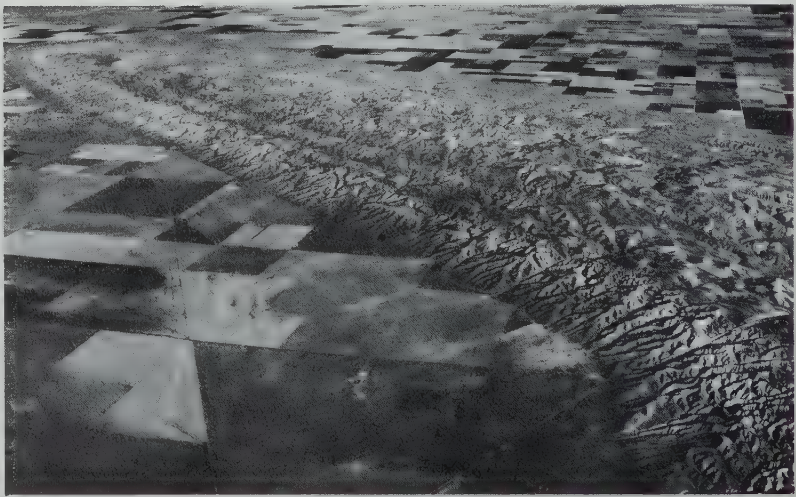


Figure 14–3
(top) The Serapeo in Italy. What is the evidence that sea level has changed?

Figure 14–4
The youngest rocks in this upfolding at Kettleman Hills, California are one to three million years old. If the rocks have been arched about 3,000 meters, what has been the average rate of uplift?

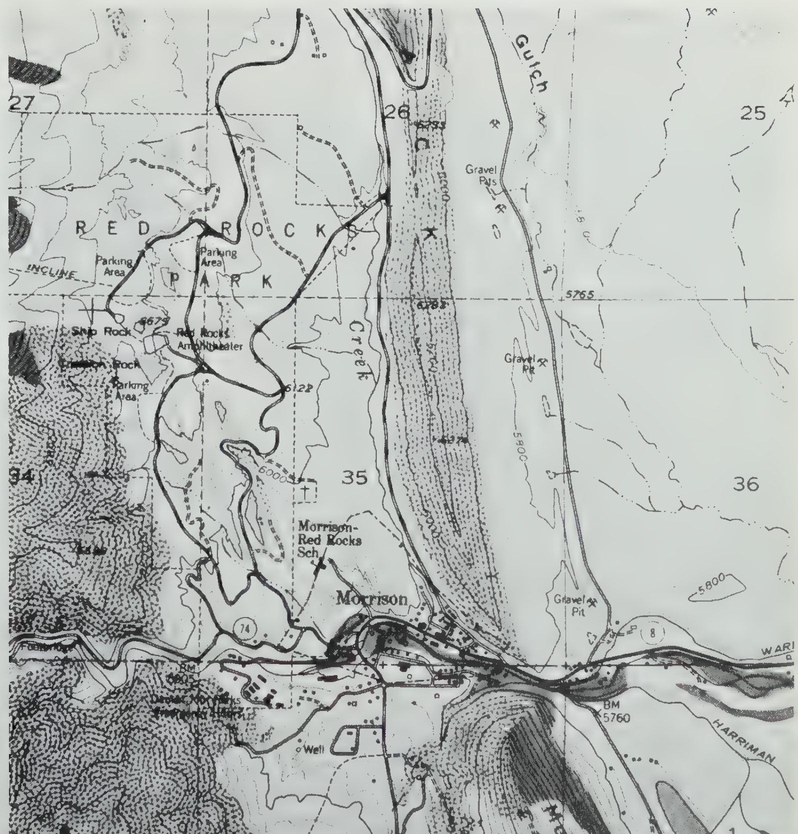


Figure 14–5
(top left) *A ground level view of the area near Red Rocks Park.*

Figure 14–6
(top right) *An aerial view of Red Rocks Park, Colorado.*

Figure 14–7
(right) *A topographic map of the same area.*

of a mountain, and a grease pencil. Use the equipment as shown in Figure 14–8. Make a series of marks 1.5 centimeters apart up one side of the box. Place the mountain model in the box and fill the box with water to the first mark. Draw a line around the mountain at the water line. Add more water up to the second mark and repeat the procedure. Continue doing this until the mountain is covered with water.

When you have finished drawing the lines, put the lid on the box. Trace the contours on the plastic sheet as you see them from above. If you close one eye, it may be easier.

5. How does your map of the model mountain compare with the topographic map?
6. How would you define a contour line?
7. Discuss the statement: "A map is a paper model of the real world."
8. How do each of the maps in Figures 14–9 and 14–10 represent the world we live in? How are they useful?

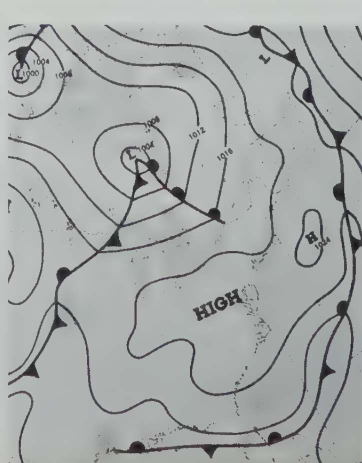
14–3 Mountains, plains, and plateaus

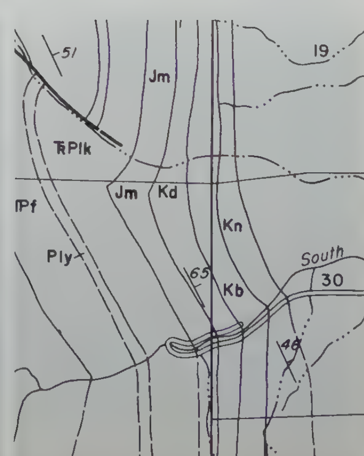
For convenience the great variety of landscapes can be divided into three main groups: mountains, plains, and plateaus. The lofty peaks of the Sierra Nevada and the Andes Mountains are places where, for the time being, the internal processes are far ahead of the external ones. These areas have lifted faster than erosion could cut them down. Great internal forces still

Figure 14–8

Figure 14–9
(*left*) *What special symbols are used in this map?*

Figure 14–10
(*right*) *Compare Figure 14–7 to this geologic map.*





struggle with each other in these high mountain ranges and produce faulting, earthquakes, and volcanism.

The Appalachian Mountains, by contrast, appear to be the worn down remains of a large mountain range uplifted long before the Rockies and Sierra Nevada. Much of this region is underlain by folded sedimentary rocks and has a distinctive landscape of alternating ridges and valleys. (See Figure 14–11.)

Plains are large areas that are either flat or gently inclined. They may occur near sea level or at elevations of several thousand feet. Some plains are formed from deposition, others are created by erosion. The plains along the Atlantic and Gulf coasts of the United States and the Great Plains east of the Rocky Mountains owe their flatness to deposits of sediments by streams. In both instances the stream deposits are underlain by older sedimentary rocks. These were deposited mainly in the sea and are now uplifted and tilted.

Most of eastern Canada is a low-level erosion plain. Much of this plain is underlain by igneous and metamorphic rocks, the remnants of ancient mountain ranges.

Smaller plains of deposition (flood plains) are found along many large streams. Flood waters and a shifting stream channel result in a plain underlain by sediment (Figure 14–12).

FIGURE 14–11
An aerial view of the Appalachians near Harrisburg, Pennsylvania.

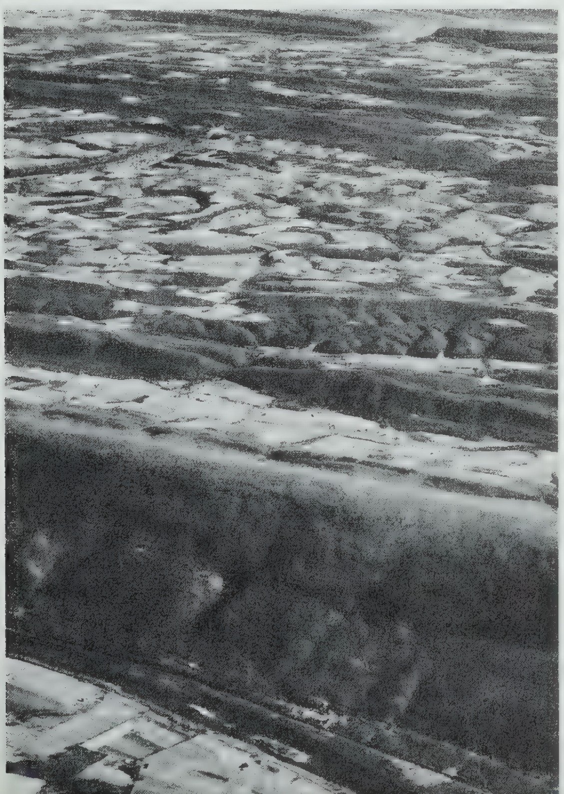


FIGURE 14–12
What evidence is there that this stream channel has shifted?

A **plateau** is a large elevated tableland. Some plateaus are produced by the piling up of lava flows. Other plateaus form when a wide area is gently uplifted. There is little folding or faulting, and the layers of rock remain nearly horizontal. A plateau may be cut by deep canyons like the Grand Canyon in the Colorado Plateau of northern Arizona (Figure 14–13).

Thought and Discussion

1. Look again at the ridge in 14–1. Suppose that uplift began at the same time for all parts of the ridge but was more rapid toward the west end. Would this account equally well for the present landscape?
2. If the processes of weathering and erosion have been acting on the land areas for billions of years, why do we find high mountain ranges today?
3. Most of the area in Figure 14–7 is underlain by sedimentary rocks. How do the landforms show the effects of tilting and differences in resistance to erosion?

Analyzing Landscapes

14–4
The parts of a landscape

Look at the landscape in Figure 14–14. Two kinds of terrain appear in this scene. One,

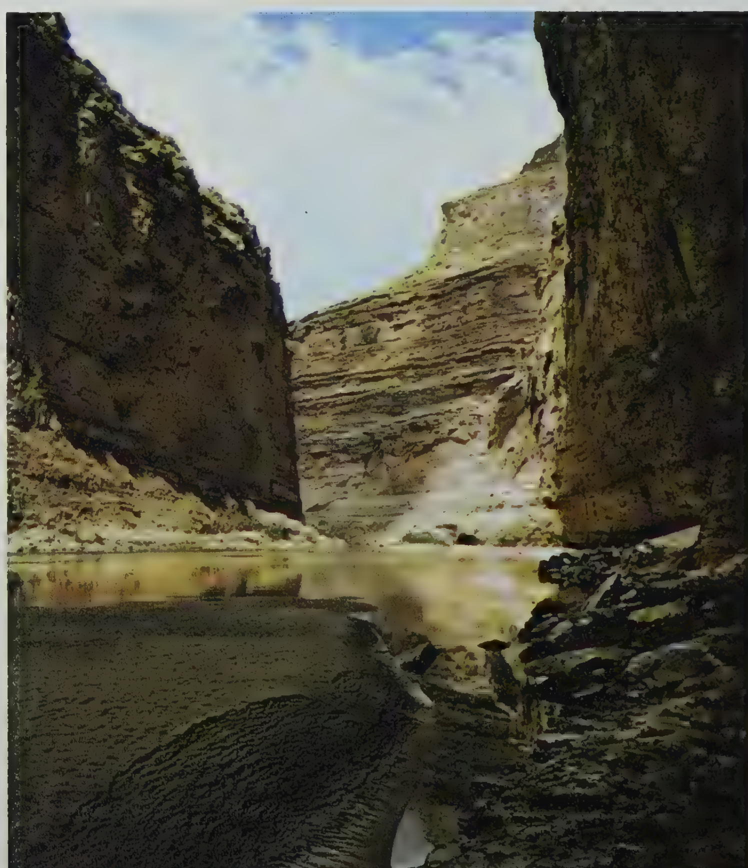


FIGURE 14–13
The Grand Canyon was eroded by the Colorado River and its tributaries. The canyon averages about 1.5 kilometers in depth and 16 kilometers in width. The river is only 50 meters wide.

FIGURE 14–14
(*top*) *Can you divide this landscape into two kinds of terrain?*

FIGURE 14–15
(*bottom*) *Compare this view of the steep east wall of Death Valley, California with the landscape above.*

mostly at the top of the scene, is rough and cut by several gullies and one major valley or canyon. This landscape is being eroded. The second kind of terrain, mostly at the bottom of the photograph, is relatively smooth. It includes the deposits on the floor of the canyon and the fan beyond the canyon's end. The fan, in turn, seems to be spread over a broader area of sediment coming from outside the area. Apparently this second area is not eroding but is receiving sediment instead.

Place a piece of tracing paper over Figure 14–14 and lightly draw a line around the borders of the picture. Now carefully trace a line across it that will separate the two kinds of terrain: land eroding and land receiving sediment. What are the major contrasts between the landscapes on the two sides of your line? How will these landscapes change?

In Figure 14–15 you see the effects of thousands of years of erosion and deposition. A road runs along the edge of the fan. Notice the patch of light-colored gravel that has been deposited on the steep fan at the end of the canyon. This is the only important addition of material to the fan in the last few decades. More sediment in this area will build it up until the stream shifts its course to another part of the fan. The gravel makes up about one thousandth of the whole deposit. If it took 30 years to add this amount of material, how long did it take to build the fan to its present size? How many factors can you think of that would affect the accuracy of your answer?

Again, it is possible to draw a line separating areas of erosion and deposition. Although these processes are sometimes interrupted and go on

very slowly by human standards, it is clear that they are changing the landscape.

How are the two landscapes in Figure 14–14 and 14–15 different? Would it surprise you to learn that the first shows an area only about one meter square? The "pole" in the photograph is a pencil. This miniature landscape with its canyon and fan was sculptured in loose soil by a single rainstorm. Thus, the two scenes differ because the second is 1000 times larger than the first and took much longer to form. Yet these two scenes have the same basic characteristics.

You can divide any landscape into areas losing material and areas gaining material. In fact, a good first step in analyzing any landscape is to distinguish between the areas of erosion and deposition.

ACTION *Observe some landscapes (large and small) in your locality. Can you identify areas that are eroding? Areas that are receiving sediments?*

Try to visit a system of valleys or gullies near your school or home. Can you identify a main valley or gully with tributaries? Sketch a map showing the relation of the tributaries to the main valley. Does the main valley have a flat bottom that is many times wider than the channel? Do the tributary stream channels meet the main channel at a common level (without rapids or water falls)? Prepare a brief description of the valleys you have observed with sketches to show sizes, shapes, and arrangements.

14–5
Investigating areas of erosion and deposition

In Section 9–7 you used a stream table to investigate erosion. Now you will investigate the miniature landscapes that are formed. Concentrate on the boundary line between erosion and deposition. What causes this line to move? Try to predict how your miniature landscape will change as the stream flows through it. Try to develop a miniature landscape like Figure 14–14 and a delta like the one in Figure 14–16.

14–6
Rates of change

When you try to read the life story of a natural landscape from the features around you, it soon becomes obvious how slowly they change. This suggests that in addition to the structure of rocks, and the internal and external processes acting on them, we must add a fourth factor that influences landscapes. This is the length of time involved.

Most landscapes do not change rapidly enough for you to watch them. Other methods must be found to interpret them. One method is to examine miniature landscapes outdoors or in a stream table. You can assume that many of the same processes operate in miniature landscapes and major ones. The rates of change, however, are faster in a miniature landscape.

Another method is to compare landscapes in different areas that have formed under similar conditions. This can help you predict how a particular structure will wear away and change. Look at the landscapes in Figure 14–17. If you

Figure 14–16
(right) How can you make a miniature version of this delta in Lake Rudolph in Africa?

Figure 14–17
Could the lower landscape develop into the upper one?

This American geographer and geologist (1850–1934) was a pioneer in the science of **geomorphology**, the study of landform development.

From ancient times until the early 19th century people believed that the landscape had always been just as we see it. In the last half of the 19th century American geologists developed important new concepts about landforms. They explored the semiarid and arid areas of the west. Landforms there owe their character to the arrangement of the rocks and to the surface processes of erosion and deposition. Davis recognized the significance of these factors. He then applied them to the study of landforms in humid climates.

Davis concluded that every landscape can be understood in terms of three factors: 1) the kind and arrangement of rocks at the surface (structure), 2) the surface processes acting on these rocks (process), and 3) the time these processes have been acting (stage). A landscape will go through distinct stages of youth, maturity, and old age, finally becoming a low eroded plain.

The importance of structure and process in the development of landforms has never been challenged. The amount of time involved in the development of any landscape remains controversial. Youth, maturity, and old age are relative terms. Some regions will pass through the stages in less time than others. The determination of the actual time involved in the evolution of landscapes remains a major problem in geomorphology.

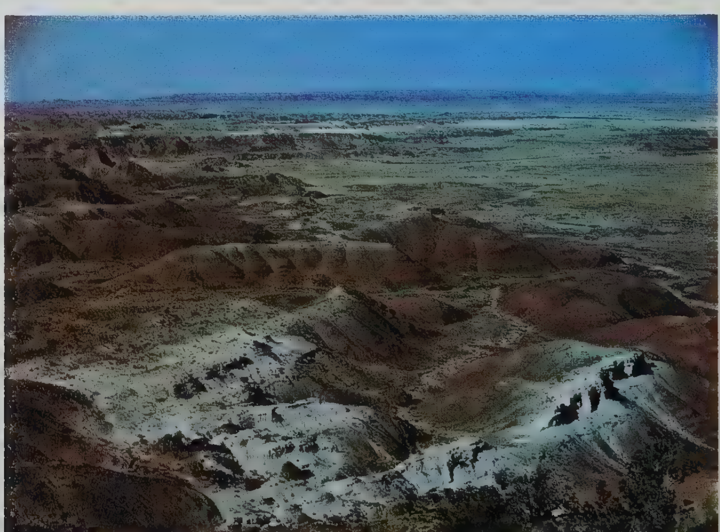


FIGURE 14–18
Steam erosion in a dry climate carved out the Painted Desert.

assume that the rocks and the climates are similar in each case, which plateau has been weathering and eroding longer?

14–7 Landscapes and climate

Even in deserts where it rarely rains, streams are the most important agent of erosion and deposition. Many tourists take pictures of the Painted Desert in Arizona to show their friends the colorful "sand dunes" there (Figure 14–18). The "dunes" are hills produced by stream erosion of brightly colored, horizontal sedimentary rocks.

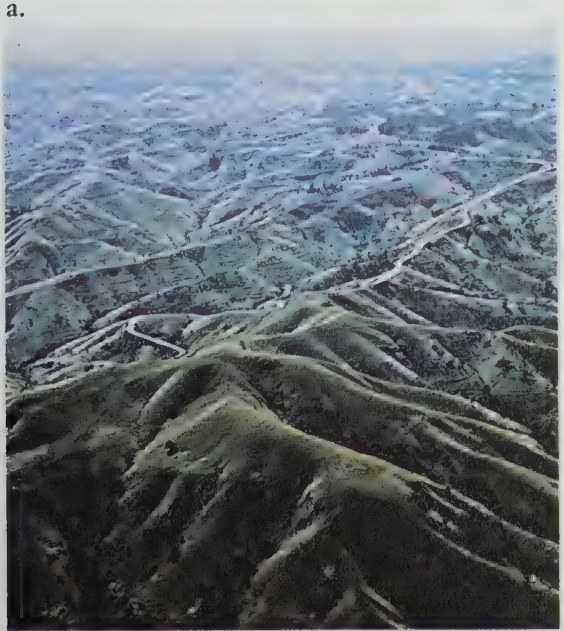
Streams are even more important land movers than glaciers. Glaciers in the high mountains of Alaska occupy valleys originally formed by streams. The glaciers merely deepen and reshape the valleys.

In humid climates (50 centimeters or more of precipitation annually) landscapes are usually covered with vegetation. The plant roots tend to hold the weathered rock in place. This favors deep and complete weathering of the bedrock and the development of soils. The landscape develops smoothly rounded slopes (Figure 14–19a).

There is less weathering and soil formation in dry regions. The landscapes are angular, and valleys tend to be narrow canyons between vertical walls. Most of us live in the more humid areas and find the landscapes of dry regions fascinating and spectacular (Figure 14–19b). If the bedrock is colorful, so much

FIGURE 14–19
Typical mature landscapes in
a. *a humid climate*
b. *a dry climate*

a.



b.

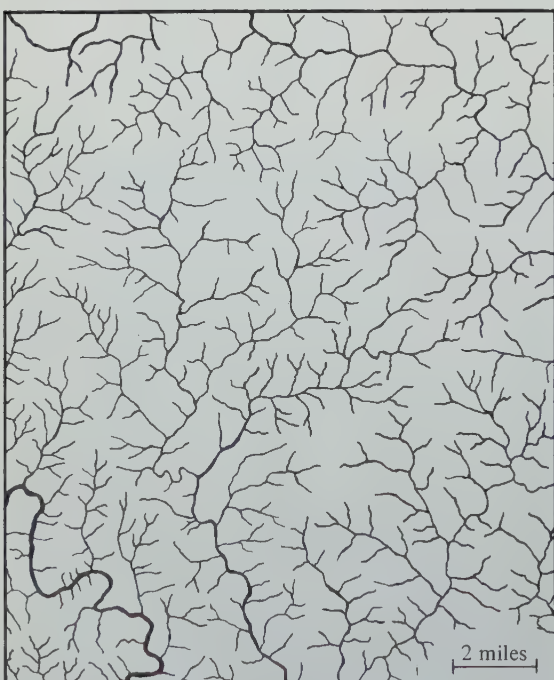
the better. Our familiar landscapes may appear dull and uninteresting by contrast.

A typical landscape consists of many valleys. These valleys form different patterns depending on how water drains into and across the land. The **drainage pattern** is usually determined by the kind of bedrock in the area. In the case of sedimentary rocks, the structure of the rocks also affects the drainage pattern.

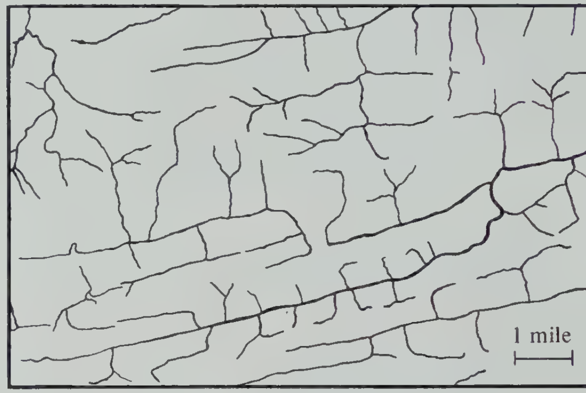
Dendritic (tree-like) **drainage** develops in areas where the bedrock has uniform resistance to erosion (Figure 14–20a). This would be true in an area of horizontal sedimentary rocks. One layer may be more or less resistant than the ones above and below. However, each layer has uniform resistance over wide areas. Plutonic rocks also have uniform resistance in any horizontal plane. Broad areas of plutonic rocks usually show dendritic drainage.

FIGURE 14–20
Typical examples of
a. *dendritic drainage*
b. *trellis drainage*
c. *radial drainage*

a.



b.



c.

Trellised drainage is typical of areas underlain by folded sedimentary rocks. Such landscapes consist of parallel ridges and valleys. The ridges are resistant to erosion, and the valleys are less resistant. Smaller tributaries flow down the slopes of the ridges to form a right angle pattern resembling a trellis (Figure 14–20b).

Radial drainage is typical of volcanic mountains. (See Figure 14–20c.) Volcanic mountains are the result of constructional processes. Can you think of other landforms that are constructional?

How would you classify the drainage patterns in the photographs?

14–8
How low can a landscape get?

If the leveling processes were the only ones at work on the earth, they would eventually remove all the high land. All irregularities in the surface would be worn down. Finally there would be produced a smooth landscape at the lowest possible elevation—one on which no particle could fall or roll anywhere. Is there such an area on the earth?

As long as a landscape remains above sea level, streams and rivers can move parts of the land to lower elevations and eventually into the ocean basins. Unless sea level itself changes greatly, the sediment will become a part of the continents again through uplift of the ocean floor during part of the rock cycle.

The lowest level to which a land area can be eroded is usually considered to be sea level. This does not mean that there is no erosion below sea level. Materials underwater may be eroded by waves and currents. You saw in Chapter 10 that the ocean floor has a strange and varied landscape. Would you expect the landforms on the sea floor to show the same patterns, shapes, and sizes as those on land?

On the land the dominant leveling agent is running water. Near the shore on the continental shelf, wave action is most important. Glaciers entering the sea can also gouge valleys below sea level. But since ice floats, this gouging cannot continue very far from land. Over most of the deep ocean bottom the only important leveling agents are turbidity currents.

No continent today is so eroded that its entire surface is nearly at sea level. However, many large areas have been almost leveled by erosion. From Washington, D.C. to Atlanta, Georgia there is a broad flat area between the Appalachian Mountains and the coastal plain. The region is underlain by igneous and metamorphic rocks. (See Figure 14–21.) The existence of these rocks at the earth's surface is proof that this area was once deep within a high mountain range. The thick cover under which these rocks formed has been removed by erosion.

ACTION *An* ***unconformity*** *is a buried erosion surface, a landscape later covered by deposition. Imagine a mountain range and the nearby areas that have been eroded to a flat surface. Horizontal layers of sedimentary rocks are later deposited on this surface. Make a sketch to show the positions of 1) the younger sedimentary*

FIGURE 14–21
Rocks formed beneath the surface were lifted into lofty mountains and later eroded to this low plain west of Charlotte, North Carolina.

rocks, 2) the plutonic and metamorphic rocks of the interior of the old mountain range, 3) the folded sedimentary rocks adjoining these, and 4) the undisturbed older sedimentary rocks beyond the area of deformation. Can you describe three types of unconformities shown in your sketch?

On the walls of the Grand Canyon you can follow the edge of an unconformity for more than 300 kilometers. (See Figure 14–22.) For most of this distance the unconformity is almost horizontal. In places this surface cuts across metamorphic, plutonic, and folded sedimentary rocks. This means there must have been a great thickness of rocks removed before the sediments of the overlying rocks were deposited. The rocks above the unconformity are about 550 million years old. To produce the nearly smooth plain over such a large area must have required a long period of erosion.

FIGURE 14–22
Locate the unconformity in the north wall of the Grand Canyon. The drawings represent stages in its development.

14–9 Other landscapes

There are unusual landscape features that you may know about. One that is of special interest is **impact craters** formed by meteorites. Over 20 impact craters have been found on the surface of the earth. These landforms do not owe their shape or origin to internal movements of the crust.

Craters that occur in moist climates usually contain lakes. Some craters look recent, like the one pictured in Figure 14–23. It may be 2,000 or 3,000 years old. Others have been so modified by weathering and erosion that they look like depressions or pits that could have formed in other ways. Proof of their explosive origin rests entirely on clues within the shattered rock.

Interest in the geology of the moon has led to intensive study of impact craters on the earth. Drilling in Meteor Crater in Arizona failed to reveal any huge chunk of a meteorite beneath its floor. From sampling the surrounding area, geologists estimate that thousands of tons of very small meteoritic particles are mixed with the soil.

Sandstone exposed below the rim of the crater is shattered and some of it has been fused to glass. Some of the quartz in the sandstone has also been converted to rare high-density forms of silica. From laboratory experiments we know that these forms of silica can be produced only by great amounts of heat and pressure. These conditions occur naturally at well over 100 kilometers below the earth's surface. A logical conclusion is that the necessary heat and pressure were supplied by the impact of a meteorite.

Meteor Crater is nearly 180 meters deep and almost 1.6 kilometers in diameter. But it has been calculated that it could have been caused by a meteorite only 25 meters in diameter

FIGURE 14–23
Meteor Crater in Arizona.

traveling 50,000 kilometers per hour! If it had traveled faster, as many meteors do, it might have been even smaller. In any case it was largely destroyed by the impact, which tossed out the lumpy deposits of light-colored rock debris.

14–10 Investigating regional landscapes

By now you should be able to examine a landscape and say something about 1) the nature of the surface rocks, 2) the effect of the internal forces, and 3) the kinds of external forces at work there. You may also be able to say whether internal or external forces dominate the landscape at present.

FIGURE 14–24

In this investigation you will study some typical mountains, plains, and plateaus in the United States. You will examine each landscape by means of 3-dimensional aerial photographs and topographic maps. Describe the landscape in each area and the processes that created the features you observe.

Procedure

Use the map provided that shows the principal landforms of the United States. Divide the country into areas of similar landscapes. Compare your landscape classification with those of other students and discuss the basis for your divisions.

With the help of the photographs and maps, answer the following questions about each area:

1. *Is the area a plain, a plateau, or a mountain?*
2. *What evidence can you find for rock cycle activity?*
3. *What leveling agent is dominant?*
4. *Which processes, uplift or leveling, have been most active in forming the landscape you see?*
5. *How has the landscape influenced man's activities.*

Mark on the landform map where you think these areas are. After you have finished all the areas, see if you still find acceptable the landscape boundaries you drew earlier.

Thought and Discussion

1. In what ways are turbidity currents on the sea floor a special case of erosion and deposition by streams?

2. What is the role of gravity in shaping landscapes?
3. In previous chapters you have studied features due to deposition or erosion by some of the leveling agents other than streams. Which of these were not influenced in size, shape, or location by earlier deposition or erosion by streams?
4. Which leveling agent is most important in shaping landforms in your locality?
5. Under what circumstances could there be radial drainage with streams flowing toward rather than away from a common point?

Unsolved Problems

One of the major difficulties in trying to understand landscapes is the way many factors interact to form them. Various specialists have examined certain aspects of the landscape with great care. The geologist knows a lot about how rocks weather and erode. The soil scientist has studied soil formation, and the biologist has learned much about soil and plant relationships. But these specialists have really only begun to study the complex ways in which all these and other elements work together.

To understand many of the details of landscape development, we need to study the combined influence of rock type and structure, soil formation, moisture, insolation, plant growth, and even human activity.

Perhaps the greatest problem is to establish the actual time it takes for landscapes to develop through youth, maturity, and old age on different kinds of rocks. How long does it take for a mountain range to become a plain?

Chapter Review

Summary

Two groups of external processes continually shape the surface of the earth. One is the weathering and erosion of solid rock, the other is the transportation and deposition of sediment. Both are closely related to the water cycle, and both depend on gravity. Together these processes make the land more nearly level.

The exact shape of the land at any particular place and time is not determined by leveling processes alone. The shape of the land also depends on events within the earth's crust. These internal processes decide the kinds of rocks exposed at the surface, how they are arranged, and whether they are being elevated.

To best interpret the shape of the land you must recognize what is going on now. Then you work back through time looking for evidence of different conditions in the past. Was a particular landscape once under ice, under the sea, or under sand dunes? If so, did this occur before, during, or after the latest uplift, tilting, or faulting? In this way you can often reconstruct a step-by-step sequence of events in the struggle between internal and external processes.

Impact craters are a special kind of landscape. While not created by normal rock cycle

processes, they are destroyed by weathering, erosion, and deposition.

Questions and Problems

A

1. How can areas of erosion be recognized? Describe such an area.
2. How can areas of deposition be recognized? Describe such an area.
3. What are the leveling processes?
4. What is the lowest elevation to which leveling processes could possibly erode the land?
5. What do unconformities indicate?

B

1. Describe the leveling processes in terms of energy.
2. Is it likely that the leveling processes will ever lower all the land to sea level?
3. Once sediments reach the ocean, can they still be eroded?
4. What does a region look like in which internal forces dominate external forces?
5. What does a region look like in which external forces dominate internal forces?
6. What evidence indicates that Meteor Crater in Arizona was created by a meteorite?

C

1. How does the kind of rock in a region help to shape the landscape in that region?
2. How do events within the crust help shape the landscape of a region?
3. Can you think of conditions under which rocks in a region would not be physically weathered?
4. Why might physical weathering stop in a region long before chemical weathering?

Suggested Readings

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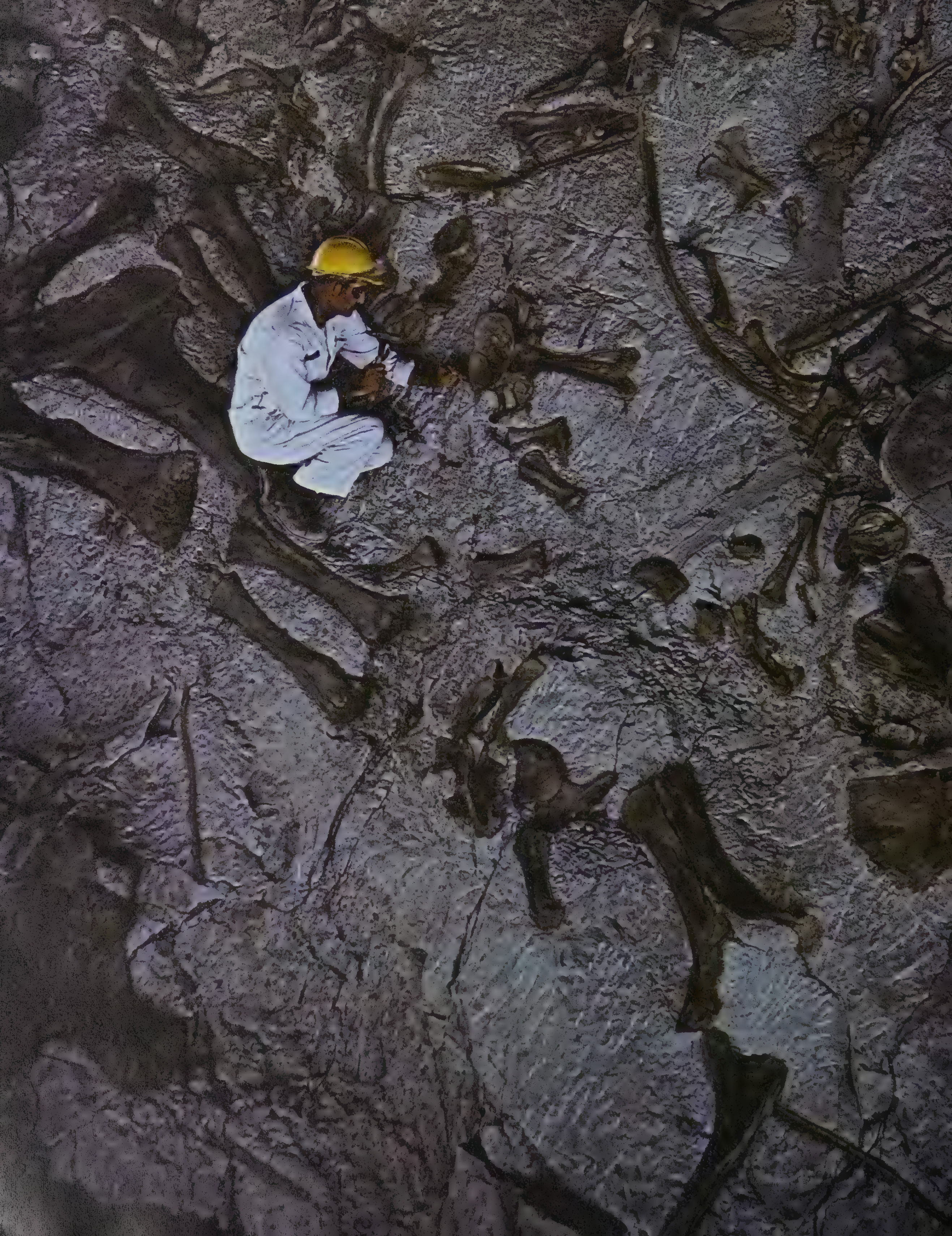
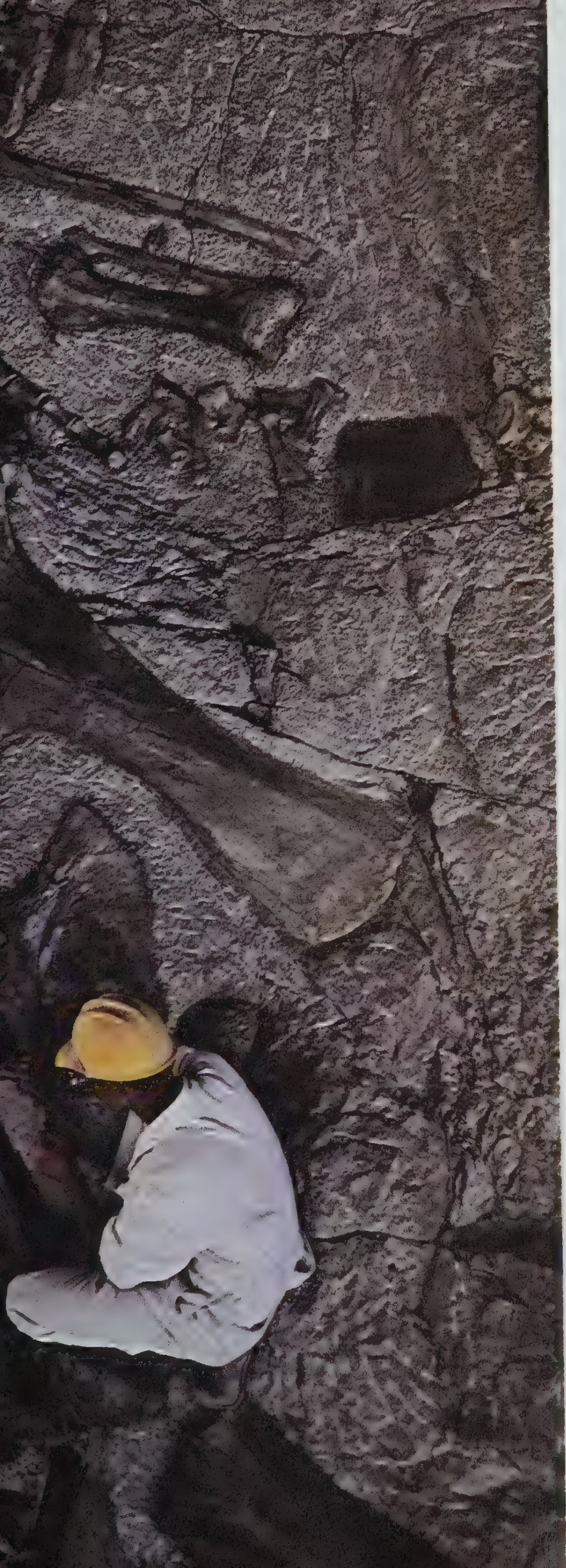




unit four

Earth's Biography


Grumman

15. Measuring Time

Everything you do is related to time. Have you ever missed a bus or part of a television program simply because you were a few minutes late? Was it because you did not allow yourself enough time or that perhaps your watch was not running properly? Stop for a minute and make a mental list of the things you do each day that depend on the measurement of time.

Time is not just a phenomenon of the present. Time has been flowing since the beginning and will continue to flow long after present generations have gone from the earth. For many centuries people wondered how old the earth was and whether or not the earth was formed at the same time as the rest of the universe. Finally, during the last 200 years, scientists have been able to answer some of these time-related questions about the history of our planet earth.

What about future time? Earth scientists are always searching for clues that might tell something about the future. They want to know how long the sun will give off enough radiant energy to sustain earthly life, when the next earthquake will occur, and what climatic changes are coming. Earth scientists can already make some predictions about the future because they have studied time past and present. In the following chapters you can learn about these predictions and how they are made.

How is Time Measured?

15–1
What is time?

Time is always with us and governs our daily lives. However, is is not easy to describe or define.

ACTION *Use any method you can think of, except your watch, to determine the duration of a five-minute period. Cover all clocks and watches in the room. Choose one student to be a timekeeper. The timekeeper will place a mark on the blackboard when you are to start to measure a five-minute period of time. When you think five minutes have passed, signal the timekeeper. The timekeeper will make a mark each time someone signals.*

Did everyone signal at the same time? What do the marks on the blackboard tell you? How did you decide when five minutes had passed? What other methods did your classmates use? What is time?

It is change that usually makes us aware of time. Change affects all parts of the earth and the plants and animals that live on it. Mountain ranges are raised on the earth's crust only to be worn down by erosion. The birth and death of a mountain range occurs over hundreds of millions of years. Animals and plants have much shorter life spans. A man's life is measured in tens of years. Changes not only make us aware of time but also provide a way to measure time.

Imagine what it would be like to live in a totally dark, air-conditioned, soundproof room without any time-measuring devices. You could not detect daily and seasonal changes in temperature and light or distinguish between day sounds and night sounds. You could not detect any change in your environment, so time would seem to stand still. (Do you think you could feel the passage of time?)

15–2
Relative time—measured time

Time is remembered by certain events. You can mark the passage of time by relating it to a series of events. If you want to construct an exact history of past events, you have to know the time between them.

ACTION *List four events of your past life. Put the most recent event at the top of your list. Now add to your list the events that one or two of your classmates listed. Try to place all of these events in the order they happened.*

Did you have difficulty in deciding whether a certain event occurred before or after other events? How long did it take for each of these events to occur? Was the time span between events the same? Did most events listed occur recently or when you were very young?

Earth scientists are interested in events that took place long before humans were around to

record them. The rocks of the earth's crust contain evidence of these events. The geologist can reconstruct the geologic history of an area by looking at the rocks there. Figure 15–1 shows an unusual exposure of sedimentary rocks. Can you tell which rock layer is oldest?

When you list events in the order they happened, you make a time sequence. You make a **relative time scale,** which is simply a "before-or-after" scale for a sequence of events. A relative time scale does not provide information about the *amount* of time involved, but it does show that one event happened before or after another.

The rock layers in Figure 15–1 have not been disturbed since they were originally deposited. This means that the top layer is younger than those layers beneath it. But how much younger is the top layer: ten million years, a thousand years, fifteen years? To answer this question, the geologist must gather more information from the rocks.

Suppose that each layer required a million years to be deposited and that five million years passed before the formation of each new layer. Now you can calculate how much older the bottom layer is than the top layer. You are able to say that the second layer is five million years older than the first, but you still cannot determine when the top layer formed. You can determine "how long" but not "how long ago."

In order to determine how long ago, you would have to measure backward from some point of reference in time. Our point of reference is *now.* When you relate these ages to the present, you have established a **measured time scale.** A measured time scale tells you how long ago an event took place.

To be most useful, events in history, whether man's history or the earth's history, should be dated in relation to the present. They can then be arranged in a relative sequence. For example, to know that dinosaurs became extinct before man appeared on earth is not as useful in constructing the history of life as it is to know that the dinosaurs became extinct about 70 million years ago. This event can be related

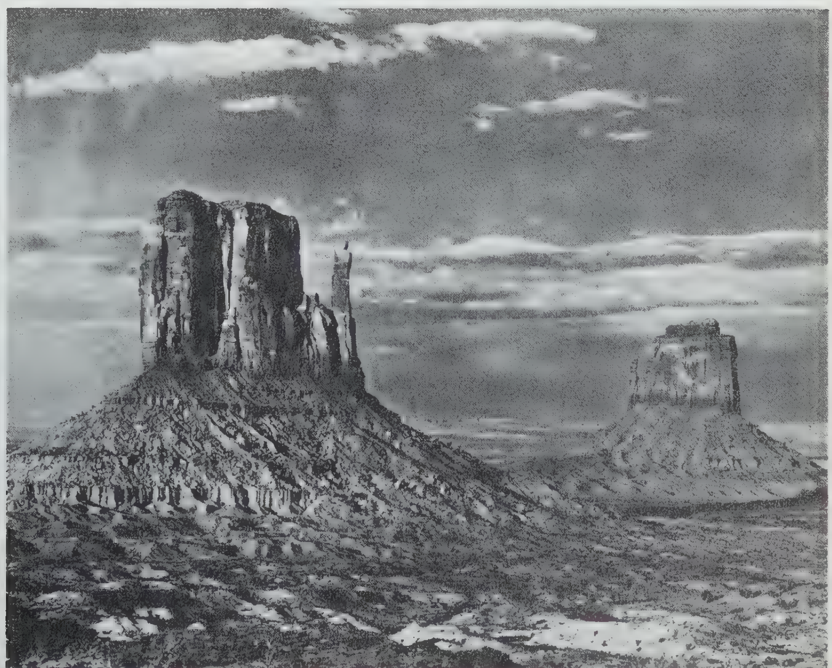


FIGURE 15–1
The two Mitten Buttes in Monument Valley, Arizona. Can you match the rock layers in the pinnacles on the left and right?

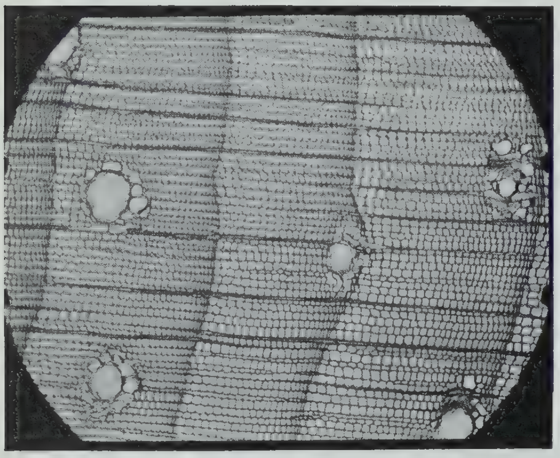
to the earliest record of man, which dates back to about two million years ago. Now you can say how many years separated man from the dinosaurs.

15–3
Clocks and calendars

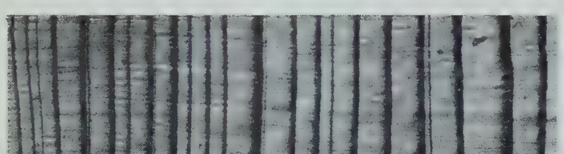
A variety of calendars and clocks are used to refer events to the past. These calendars and clocks permit us to keep track of years, months, days, hours, minutes, and seconds. Two of these units, the year and the day, are based on natural events. Other time units are man-made. An hour is 1/24 of a day, a minute is 1/60 of an hour, and a second is 1/60 of a minute or 1/86,400 of a day.

Clocks and calendars work well for current events. But what about events that took place ten thousand years ago or a million years ago?

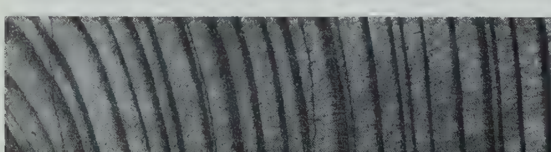
a.



b.



c.



d.

e.

FIGURE 15–2
a. *A magnified section of wood showing cells. How many years of growth show?*
b., c. *growth rings from two different trees. Do they match at any points?*
d. *growth rings in a clam shell.*
e. *sedimentary layers.*

Man-made clocks have been in existence for a very short time. Thus scientists must use natural clocks for a record of events that occurred millions of years ago.

The day, the seasons, and the years are natural units of time resulting from motions of the earth. It is reasonable to assume that the earth has been rotating on its axis and revolving around the sun since the solar system formed. Therefore, evidence of seasonal change might be recorded in the rock and fossil records.

ACTION *Look at Figure 15–2. See if you can find signs of changes that have happened in the recent past. Figure 15–2a is a magnified view of tree rings. Which wood cells represent spring growth and which wood cells represent summer growth?*

Might the two trees shown in Figure 15–2b and 2c have lived at the same time during any part of their lives? What evidence is there for seasonal changes in the shell growth and the sedimentary layers in Figure 15–2d and 15–2e?

In the preceding ACTION you examined plants, animals, and rocks that have recorded changes at various times in the past. These clocks provide information about climatic conditions for short spans of time. However, their recording period is too short for establishing earth events millions of years ago.

Thought and Discussion

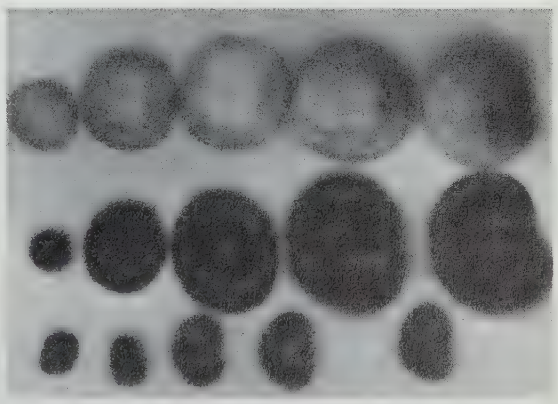
1. In a time-ordered sequence of events, event A happened before event B, which in turn happened before event C. Event D, however, happened before event B, but after event A. Can you represent these events in their proper order. Place the most recent event at the top of your list.
2. Can you think of any events that do not involve change?
3. Why is it important that earth scientists be able to determine relative and measured geologic time?
4. How would you define time?

Geologic Clocks

15–4
Radioactive elements and atomic clocks

In 1896 Henri Becquerel (On-REE Beh-KREL), a French physicist, placed an unexposed photographic plate next to a piece of uranium compound in his darkroom. Later when he wanted

FIGURE 15–3
These radioactive tomato seeds took their own picture by exposing nearby film.



to use the photographic plate, he found that it had been partially exposed, and an image was already on it. This puzzled Becquerel for the plate had been carefully protected from light in the darkroom. He'd discovered certain natural substances, such as uranium, give off energy that could expose a photographic plate. This discovery led others, like Marie and Pierre Curie, to research this mysterious property, which is now called radioactivity.

Action *Obtain a small amount of uranium ore or a specimen of uranium-bearing mineral from your teacher and place it in the cloud chamber. You used a cloud chamber in Section 3–6. Observe the emission of particles from your radioactive specimen. Then place the uranium specimen in a drawer next to an unexposed piece of cut film or a roll of film. Be sure that the film is tightly wrapped so light cannot seep in. After the radioactive substance and the film have been next to each other for a few days, have the film developed.*

The nucleus of an atom is composed of protons and neutrons. The positively-charged protons of the nucleus repel each other, and the uncharged neutrons add mass to the nucleus. The forces that bind the nucleus together are very strong and not fully understood. The balance between repelling and binding forces in the nucleus of some kinds of atoms is often disturbed. As a result, the nucleus splits apart and energy and charged particles are emitted. This process is called **radioactive decay.**

Some of the minerals found in the earth's crust contain radioactive elements. These elements decay to more stable elements at a known rate. Therefore, radioactive minerals can be used to date events in the earth's past.

15–5 Investigating radioactive decay rates

*All of the nuclei of radioactive elements do not decay at the same time. The decay process involves chance. Although atoms cannot avoid decay, it is impossible to tell when it will happen for any particular nucleus. Since even a small sample of a radioactive element contains billions of atoms, the average rate of decay can be determined. Once this average rate is found, calculations can be made to find out how long it would take for 50 per cent of the atoms to decay. This time is called the **half-life.** The half-life of radioactive substances varies from a fraction of a second to billions of years.*

To illustrate the role of probability in radioactive decay, you can develop the following simple model.

Procedure

Place the markers into a square or rectangular box with one side marked. Shake the box vigorously. Remove only those markers that point to the marked side and assume that these "atoms" have decayed. Record the number of markers remaining in the box as Trial 1. For each trial,

shake the box with the remaining markers. Continue until the box is empty. Make a graph by plotting the number of markers left in the box versus the trial number.

Next, do the same thing with ***two*** *sides of the box marked, and again with* ***three*** *sides marked. Using your three graphs, answer these questions. Assume that each trial represents 100 years.*

1. *What was the half-life for each model?*
2. *How did you change the half-life in the models?*
3. *What difference would it make in your results if a classmate added some markers to the box during your investigation? Try it!*

15–6 Using atomic clocks to measure geologic time

Although most 18th and 19th century earth scientists thought the earth was very old, proving its great age was not a simple matter. One of the earliest attempts to date the earth was made in 1715 by an English astronomer, Edmund Halley. He correctly assumed that the sea was originally fresh water that gradually became saltier as it aged. Halley knew that the salts in the sea had been dissolved from rocks and carried to the sea by streams. This led him to believe that the total amount of salt in the sea might be a clue to the age of the oceans. In turn, the age of the oceans would provide an estimate of the age of the earth.

Halley was unable to try his salinity method of dating because he did not have the necessary data. But in 1898 John Joly, an Irish scientist, believed that he had assembled enough information to make a reasonable estimate of the age of the ocean. His calculations suggested that it had taken from 80 to 90 million years for the oceans to reach their present salinity. And since it formed before the sea, the earth was bound to be more than 80 million years old.

During this same period, other geologists tried to learn how long it took to form all the sedimentary rocks in the earth's crust. They studied the rates of accumulation of various sediments. They estimated how much time was required to deposit the sediment needed to

Figure 15–4

form one meter of sandstone, limestone, shale, and other rocks. Then they examined exposed rocks all over the world. They tried to determine the maximum thickness of rock formed during each period of geologic time. The thicknesses of all the rock beds were then added together. Finally, the time needed to deposit all the sediments was calculated. Estimates of the earth's age ranged from less than 100 million to more than 400 million years.

The results were far from accurate, for there were too many factors involved. For one thing, sediments accumulate at different rates in different environments. Also, it is impossible to figure out the time represented by gaps in rock layers caused by erosion. These old, buried erosion surfaces may span tens of millions of years. They indicate missing parts of the geologic record.

Most early physicists believed they could prove mathematically that the earth could be no more than 20 to 40 million years old. The physicists based their method on the idea that the earth cooled from a molten state. They determined the temperature of rocks of the earth's crust and an approximate rate of cooling for the earth. Using these figures, they then calculated the earth's age. As additional support, they pointed out that there was no known source of energy that could keep the sun hot for more than 20 million years. It was not logical to assume the earth was older than the sun.

The discovery of radioactivity by Becquerel strengthened the geologist's argument. Dates from radioactive minerals helped convince the physicists that the earth was much older than they had thought.

Discovery of the property of radioactivity soon led to other discoveries about radioactive substances, including rates of decay, the amount of energy generated, and products of the decay process. In 1907 the American chemist and physicist, B. B. Boltwood, discovered that uranium decays, forming lead as the final product. Boltwood concluded that the age of a particular mineral can be found, if you measure the amount of the parent material (uranium) in it and the amount of the decay product (lead). You would also have to calculate the rate of decay of the parent material.

One popular radioactive dating method is based on the breakdown of uranium-238 (^{238}U). Uranium-238 decays through a series of 14 steps, ending up as lead-206 (^{206}Pb). As the breakdown from uranium progresses, the amount of lead increases. The rate of decay of ^{238}U and other unstable elements used for dating have been precisely determined and found to be constant throughout geologic time.

After a mineral containing uranium atoms is formed, the products of uranium decay begin to accumulate in the mineral. The age of the mineral is calculated by determining the ratio of the parent material (^{238}U) to the end product (^{206}Pb). Elaborate analytical equipment must be used for determining uranium to lead ratios. In applying this method, it is assumed that none of the lead escapes from the mineral, that no outside lead is added, and that no lead from a non-radioactive source was present to begin with. If any of these conditions have

affected the sample being tested, the results will not be accurate. Can you suggest how the ages obtained in dating three samples might be affected if each of the samples was altered in one of the above ways?

The half-life of ^{238}U is incredibly long: 4.51 billion years. Therefore, ^{238}U is used to date very old rocks in the earth's crust. Some intrusive igneous rocks from Canada and Africa, dated by this method, were found to be around 3.5 billion years old. These are the oldest reliably dated rocks known. To date events that have occurred during the last 30,000 to 40,000 years, a radioactive element having a much shorter half-life must be used. Because carbon-14 has a half-life of 5,700 years it has been used widely to date relatively recent events.

Radiocarbon (^{14}C) is continuously forming in the earth's upper atmosphere. This happens naturally as nitrogen atoms (^{14}N) are bombarded by high energy cosmic rays (Figure 15–6). These cosmic rays are fast moving nuclei that reach the earth from space. Once the carbon-14 atoms are formed, they can unite

FIGURE 15–5
The Dead Sea scrolls were discovered by archaeologists in a cave in Jordan. Which dating method was probably used to show that they are about 2,000 years old?

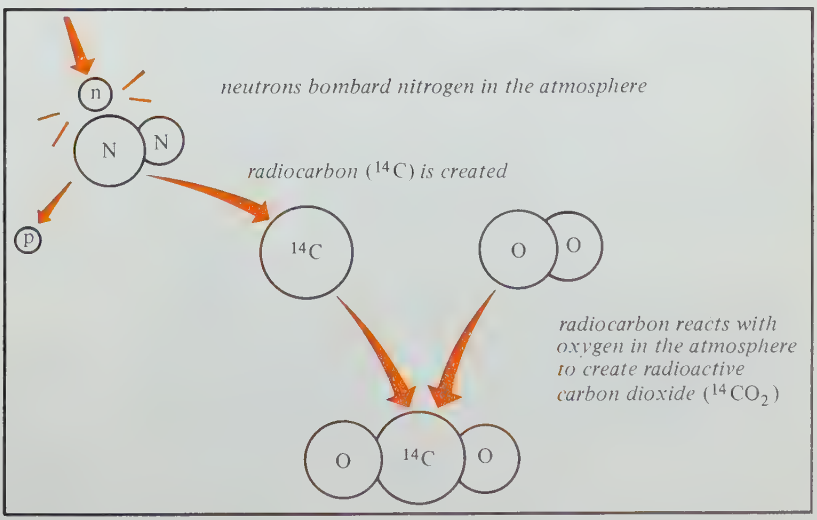


FIGURE 15–6
Radiocarbon atoms form in the upper atmosphere and enter the carbon cycle.

Figure 15–7
$^{14}CO_2$ enters a tree. When the tree dies and decays, the amount of ^{14}C in the wood begins to decrease. How does the ratio of ^{14}C to ^{12}C change in time?

with oxygen to form carbon dioxide. This reaction is part of the carbon cycle.

The radiocarbon dating method has been used to date thousands of different specimens of organic matter including wood, bones, hair, and even old food. Figure 15–7 summarizes the events behind radiocarbon dating.

Other radioactive dating methods are also used by scientists to determine the ages of rocks. Some of the other methods can be used more widely because they are based on elements that are more abundant in most rocks than ^{238}U and ^{14}C.

Thought and Discussion

1. What information besides chronologic sequence can be obtained from tree rings?
2. Can you define the term half-life? Do all radioactive elements have the same half-life?
3. What effect does the radioactive decay of unstable elements in the earth's crust have on the rocks surrounding them?
4. Which method of radioactive dating is used for relatively recent events? Why?

The Geologic Time Scale

15–7
Organizing the rock record

It took more than 200 years for geologists to put together a special Geologic Time Scale

FIGURE 15–8
Bristlecone pines are among the oldest living things on earth. They provided a double check on radiocarbon dating of objects a few thousand years old. Their growth rings show that radiocarbon formation has not been constant during the earth's recent history. Many ^{14}C dates have had to be revised.

Figure 15–9
The Geologic Time Scale

ERA	PERIOD	EPOCH	EVENTS IN THE HISTORY OF LIFE	OTHER IMPORTANT EVENTS
CENOZOIC	Quaternary	Recent (Holocene) (10,000)		Modern horse develops in North America, then dies out. / Ice ages / Grand Canyon carved. / Pacific Coast Ranges formed.
		Pleistocene (2,000,000)	*Earliest man*	
	Tertiary	Pliocene (11,000,000)		
		Miocene (25,000,000)	*Rapid spread and development of grazing mammals*	
		Oligocene (40,000,000)	*Earliest elephants*	
		Eocene (60,000,000)	*First rhinoceroses and camels*	
		Paleocene (70,000,000)	*First primates and horses*	*Uplift and folding of Western Geosyncline*
MESOZOIC	Cretaceous (135,000,000)		*Extinction of dinosaurs* / *Great development and spread of flowering plants*	*Half of North America covered by seas.*
	Jurassic (180,000,000)		*First birds and mammals* / *Dinosaurs at their peak*	*Dinosaurs, marine, and flying reptiles*
	Triassic (225,000,000)			*Arid climates in much of western North America*
PALEOZOIC	Permian (270,000,000)		*Mammal-like reptiles*	*Ice ages in Southern Hemisphere* / *World climate much like today* / *Deserts in western United States*
	Pennsylvanian (305,000,000)		*First reptiles* / *Spread of "coal plants"* / *Large insects*	*Tropical climate in United States* / *Uplift and folding of Appalachian Geosyncline*
	Mississippian (350,000,000)		*Forests of "coal plants"* / *Sharks abundant*	*Widespread flooding of North America. Much limestone deposited.*
	Devonian (400,000,000)		*First amphibians* / *First forests* / *Trilobites*	*Filling of Appalachian Geosyncline and Western Geosyncline*
	Silurian (440,000,000)		*First air-breathing animals* / *First land plants*	*Deserts in eastern and central U.S.*
	Ordovician (500,000,000)		*Trilobites at peak* / *First vertebrates (fish)*	*Widespread flooding of North America by seas*
	Cambrian (600,000,000)		*Marine shelled invertebrates common* / *First abundant animal fossils*	
PRECAMBRIAN	Proterozoic (2,500,000,000)		*Marine invertebrates probably common, few with shells.* (1,200,000,000)	*Glaciation—probably worldwide* / *Many geosynclines filled, uplifted, and eroded.*
	Archeozoic (4,500,000,000)		*Earliest plants (marine algae)* (3,200,000,000)	

Numbers refer to time in years B.P. (Before Present) since the beginning of the era, period, or epoch.

(Figure 15–9). The Geologic Time Scale subdivides geologic history into units of time based on the formation of certain rocks.

The largest of these time units is called an **era.** Each era is divided into **periods,** which in turn may be divided into smaller units called **epochs.** When placed in proper order, these time units form a geologic calendar.

When divisions of earth history are compared to the divisions of your textbook, an era is like a unit, a period is like a chapter, and an epoch is like a section. The chief difference between these is that the time scale divides time, and the book divides information.

Real progress in organizing the rock record began late in the 18th century. During this period, the basic ideas of superposition, uniformitarianism, and fossil correlation were proposed.

James Hutton was the first to clearly state the idea of superposition. He examined sediments accumulating along the seashore. He recognized that the layers deposited first were covered by layers deposited later. The idea that the oldest bed in a sequence of rock layers is the one on the bottom is called the **principle of superposition.** The basic concept has been used by geologists to work out sequences of rock layers in all parts of the world.

In addition to superposition, Hutton proposed another principle that has proved basic to our understanding of earth history. He observed that features of old sedimentary rocks, such as mud cracks and ripple marks, were duplicated in sediments he saw being deposited in his own time. From his observations Hutton concluded that the processes affecting the earth today also affected the earth in the past. Therefore, the present can be used as a key to the past. This is often referred to as the **principle of uniformitarianism.**

The other fundamental idea is that fossils may differ from one layer of sedimentary rocks to the next. These different fossils can be used to identify the beds that contain them. This idea, called **fossil correlation,** was first recognized by William Smith, an English engineer. Smith was primarily concerned with how to use this knowledge in building roads and canals.

The work of Hutton, Smith, and European scientists during the late 1700's and the early 1800's led to a general understanding of the relative ages of most rocks on the earth's surface. This was done by first working out the relative ages of rocks in many areas. The series of ages obtained locally were then matched, or **correlated,** with series found in other areas. The geologic history of large regions can be determined using this technique.

15–8 Investigating the Geologic Time Scale

The dividing lines between eras, periods, and epochs are based on recognizable changes. These include changes in life forms and episodes of mountain building. For example, the extinction of dinosaurs separates the Mesozoic Era from the Cenozoic Era. The uplift of the Appalachian Mountains ends the Paleozoic Era.

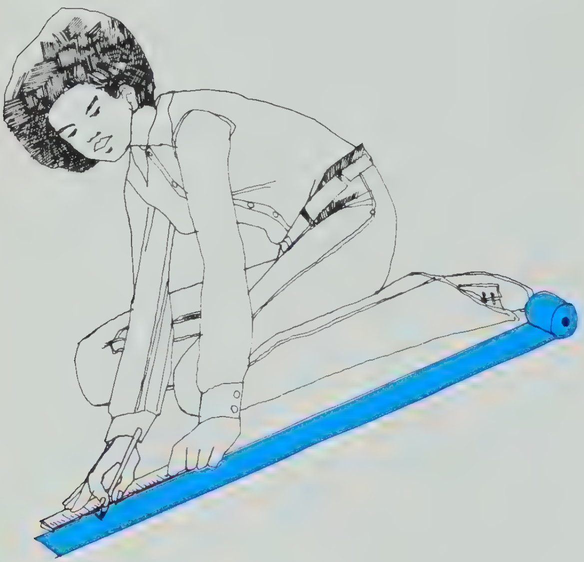
The dividing line is never a sharp one. It is more a zone of transition in time.

It is difficult to understand such long periods of geologic time when a human's life span may be only 70 years. You can make a model to help you visualize the great age of the earth.

Procedure

Examine the list of events in Figure 15–11. Then decide how to represent these events in a time-ordered sequence. A roll of paper tape will be provided on which to plot your model.

Figure 15–10



15–9 Calibrating the Geologic Time Scale

As more rocks are dated by radioactive methods, earth scientists learn the actual ages of the events on the Geologic Time Scale. The dates that are generally accepted for the major units of geologic time are the same as those on your tape from Investigation 15–8.

To see how earth scientists calibrate the time scale, let us examine a simplified version of a technique they use. In Figure 15–12 you can tell that the granite is younger than rock unit X because it intrudes into unit X. The rocks in unit X are older than those in unit Y, which

Figure 15–12
Apply the principle of uniformity of process to determine the relative ages of rock units X, Y, and Z.

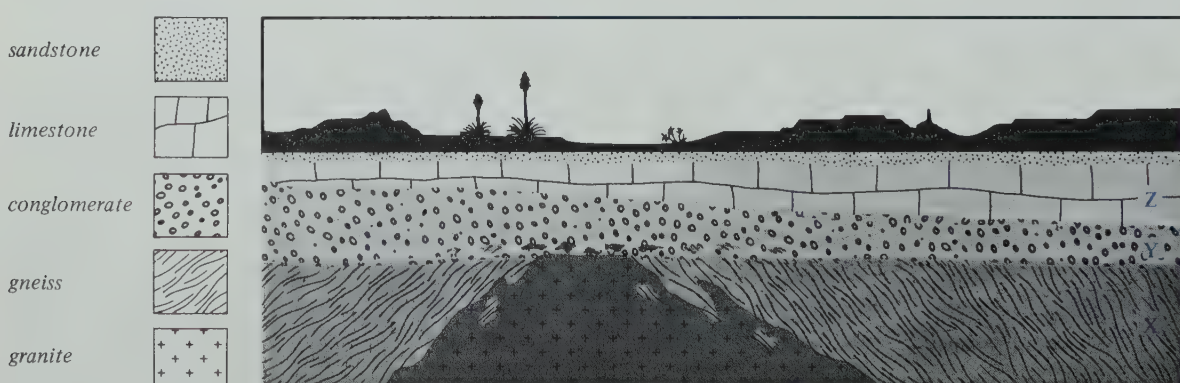


FIGURE 15–11
Ages of Events in Years Before Present

1. Oldest known rocks, 3.5 billion years ago.
2. First known plants (algae), 3.2 billion years ago.
3. First known animal (jellyfish),1.2 billion years ago.
4. Beginning of the Cambrian and first abundant fossils, 600 million years ago.
5. Beginning of the Ordovician and first backboned animal, 500 million years ago.
6. Beginning of the Silurian and the first land plants, 440 million years ago.
7. Beginning of the Devonian and the first amphibians, 400 million years ago.
8. Beginning of the Mississippian, 350 million years ago.
9. Beginning of the Pennsylvanian and the first reptiles, 305 million years ago.
10. Beginning of the Permian, 270 million years ago.
11. Beginning of the Triassic and the first dinosaurs, 225 million years ago.
12. Beginning of the Jurassic and first mammals, 180 million years ago.
13. First birds, 160 million years ago.
14. Beginning of the Cretaceous, 135 million years ago.
15. Beginning of the Paleocene and first primates, 70 million years ago.
16. Beginning of the Eocene, 60 million years ago.
17. Beginning of the Oligocene and first elephants, 40 million years ago.
18. Beginning of the Miocene, 25 million years ago.
19. Beginning of the Pliocene, 11 million years ago.
20. First man-like animals, 2 million years ago.
21. Beginning of the Pleistocene and ice ages, 1 million years ago.
22. Last ice age, 10,000 years ago.

    Convert the following to years before the present:

23. Mount Vesuvius eruption destroys Pompeii, A.D. 79.
24. First U.S. satellite orbited, 1958.
25. First man on the moon, 1969.
26. Last New Year's Day.
27. Today.

James Hutton (1726–1797) was one of the true pioneers of earth science. His ideas about the earth were so revolutionary that he has been called the "father of geology." Trained as a physician, Hutton lived in Edinburgh but traveled widely in Britain. For over 30 years the Scottish physician-turned-geologist carefully studied the earth's surface.

Hutton had an inquiring mind and made accurate field observations. But although his interpretations were remarkably accurate, scientists of the 18th century were skeptical of his ideas. Worse yet, his dull and wordy style of writing hampered his attempts to explain his startling findings.

Luckily, one of Hutton's friends, John Playfair, recognized the potential of Hutton's poorly written work. Playfair was professor of mathematics and philosophy at Edinburgh and was a skillful writer with a knack for the logical presentation of ideas. His book, *Illustrations of the Huttonian Theory of the Earth*, not only simplified Hutton's statements, but included some of his own ideas. Published in 1802 (five years after Hutton's death) Playfair's book was widely read and accepted by geologists of the day.

Thanks to Playfair, the budding science of geology was revolutionized by Hutton's interpretation of earth materials and geologic processes. In the light of evidence from his field studies, Hutton concluded that the natural processes that are now changing the earth's surface have operated rather uniformly and continuously in the geologic past. Or, more simply stated: the present is the key to the past. Now known as the principle of uniformitarianism, or the principle of uniformity of process, this idea lies at the very heart of most geologic interpretation. Equally important, Hutton also clearly recognized the significance of time—immeasurably vast spans of time—in the operation of geologic processes.

With the Huttonian concept of uniformitarianism to guide them, and with a better understanding of the immensity of geologic time, students of earth history were at last able to explain logically many of earth's features. But Hutton's uniformitarian principle did more than provide the unifying concept that geology so badly needed. It is also one of geology's outstanding contributions to modern scientific thought.

contains weathered pieces of the granite. You can also tell that the granite is older than unit Z. But you cannot tell how long ago the events took place. You need some actual age determinations. Assume that tests show that the granite is 150 million years old and unit Z is 130 million years old. Now what can you determine about the age relationships of the rock units X, Y, and Z in the diagram?

The oldest rocks dated so far are around 3.5 billion years old. These rocks have been intruded into still older rocks which have not been dated. Additional evidence of the great age of the earth has been obtained from meteorites that contain radioactive elements. These meteorites have been dated and appear to be more than 4.5 billion years old. How does this age compare with that of the oldest rocks found in the earth's crust?

Thought and Discussion

1. Were the earliest methods of classifying geologic time relative or measured? Why were such methods used?
2. How does the correlation of fossil species relate to the development of a Geologic Time Scale?
3. How could you develop a Geologic Time Scale for your local area if one were not available?

Unsolved Problems

Will we ever know the exact age of the earth? Radioactive age determinations of some meteorites are about 4.5 billion years old. Is this the age of the earth? Scientists also want to know how long it took for the earth's crust to form and what is the age of the ocean basins.

By dating events more accurately, man will be better able to determine the rates of geologic processes such as uplift and erosion. Were these rates slower or faster in the past? Knowledge of past rates of processes will give us a clearer picture of the development of the earth as we know it now.

Finally, are the oldest rocks in each continent about the same age? If not, which continent is the oldest? Which continent is the youngest?

Chapter Review

Summary

Time is measured by events. It can be considered in a relative sense—old, older, oldest—or it can be considered as a measure of duration (how long) or age (how long ago). Earth scientists consider time in all these ways. Long before the discovery of radioactivity in 1896, earth scientists were able to develop a Geologic Time Scale that was workable on a world-wide basis. This time scale was worked out on the basis of relative ages. Three basic ideas—the principle of superposition, uniformitarianism, and correlation by fossils—were used in establishing the relative ages of rocks of the earth's crust.

With the discovery of the property known as radioactivity, it was possible to date events that occurred at various times in the distant past. Some minerals that occur in the rocks of the earth's crust contain unstable elements whose atomic nuclei start to decay as soon as they are formed. In the process of decay, energy is released and unstable elements are gradually transformed into stable elements.

Several radioactive dating methods including the uranium-lead ratio method and the carbon-14 method are widely used in determining the ages of rocks of the earth's crust. Carbon-14, which has a half-life of 5,700 years, can be used to date very young rocks and objects of historic time. Other methods are used for dating much older rocks, some as old as 3.5 billion years. Based on the ages of these rocks and on other evidence, earth scientists now believe the earth to be at least 4.5 billion years old. Geologic time is incredibly long, especially in comparison to the short time that man has been on earth.

Questions and Problems

A

1. Scientists believe that the earth's rate of rotation is slowing down as a result of the moon's gravitational attraction. What effect will this change have on the length of a day? the length of a year?
2. Why is carbon-14 not used for dating rocks of Paleozoic age?
3. Why is carbon-14 more useful in dating certain earth materials than other dating methods?
4. How old are the oldest rocks dated thus far? Do these rocks represent the original crust of the earth?

B

1. Why were earth scientists unable to prove before the year 1907 that the earth was more than 20 to 40 million years old?
2. Why were many of the early age determinations obtained by the uranium-lead dating method inaccurate?
3. Why is it necessary to study carefully both the rocks and the geology of an area from which a sample for radioactive dating is obtained?
4. If rocks on other continents contain the fossil remains of large dinosaurs, would they be approximately the same age as rocks in the United States containing similar fossils?

C

1. Some charcoal and charred, broken bones of deer and rabbits were dug from beneath several feet of sand and gravel along the banks of a river. Analysis of the charcoal in a laboratory showed that one-eighth of the ^{14}C remained in the charcoal. How old is the charcoal? Reconstruct the sequence of events that may have taken place at the site of this find.

Suggested Readings

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16. The Record in the Rocks

In 1893 the captain of the sailing ship Jason set foot on an Antarctic island largely covered by ice. Imagine his surprise when he found petrified ferns, snails, and trees in the rocks there!

Similar discoveries were made by members of Admiral Richard E. Byrd's expedition to the Antarctic in 1935. They found fossilized tree trunks about a half meter in diameter and beds of coal that were separated by layers of shale and limestone. Coal has also been found on the Arctic island of Spitsbergen. And in 1969 and 1970 the remains of reptiles were found in Antarctica. Most modern relatives of these fossilized plants and animals live only in tropical and subtropical climates. Climates must have been different when these earlier organisms lived.

Perhaps you have read that rivers cut long deep trenches like the Grand Canyon in the earth's surface. Did you know that seas covered the Grand Canyon area millions of years ago? Great thicknesses of sediment were deposited on the floors of these ancient seas. The rocks formed from these sediments can be seen in the walls of the Grand Canyon today. These layered rocks are like "pages" in the history of the earth.

A geologist reconstructs the geologic history of an area from clues found in the rocks themselves. Like a detective solving a crime, he must gather clues, assemble them, and finally determine what they mean. In this chapter you will have a chance to become a "geo-detective." You will become familiar with the various types of evidence found in the rock record and will use this information to reconstruct certain events that took place in the geologic past.

Learning to Read the Record

16–1
Clues to the origin of rocks

Imagine that you are examining a rock outcrop (Figure 16–1a). This picture gives an overall view of the outcrop and the surrounding rocks. Move closer (Figure 16–1b) to learn more about the nature of the rocks. A detailed examination (Figure 16–1c) reveals their texture and provides additional information about their history.

Trace minerals (minerals that are usually present in small quantities) often can be used to help determine the origin of sedimentary rocks. For example, imagine garnet grains are observed in sandstone. If the only other garnets in the area occur in an exposure of metamorphic rock 40 kilometers to the north, it is likely that rock was the source of at least some of the sediment. This interpretation would be strengthened if you followed the sandstone bed back toward the rock and discovered that the percentage of garnet increased as you approached the metamorphic rock.

Most sedimentary rocks are composed of fragments of other rocks. The size of these sedimentary grains may be a clue to the speed of the depositing current. The shape of sedimentary particles can also indicate something about their past. Rock fragments may be rounded and smoothed as they are transported by water, wind, or ice.

Sedimentary layers may contain fossils. These rocks may even consist entirely of the broken

Figure 16–1
Zeroing in on a rock outcrop.

a.

b.

c.

shells of marine organisms. Ancient coral reef deposits, for example, are built almost entirely of fossils. We assume that these organisms lived in warm environments like their present-day relatives. Thus, these fossils tell us about environments that existed in the geologic past.

The texture of an igneous rock depends on how it formed. A fine-grained crystalline or glassy texture usually means that the lava cooled rapidly. A large-grained crystalline texture normally indicates that the rock cooled slowly, and in many cases, deep beneath the earth's surface. Metamorphic rocks may also contain clues to their origin. Most metamorphic rocks have been subjected to high pressure, resulting in flaky, crystalline textures such as those observed in schists.

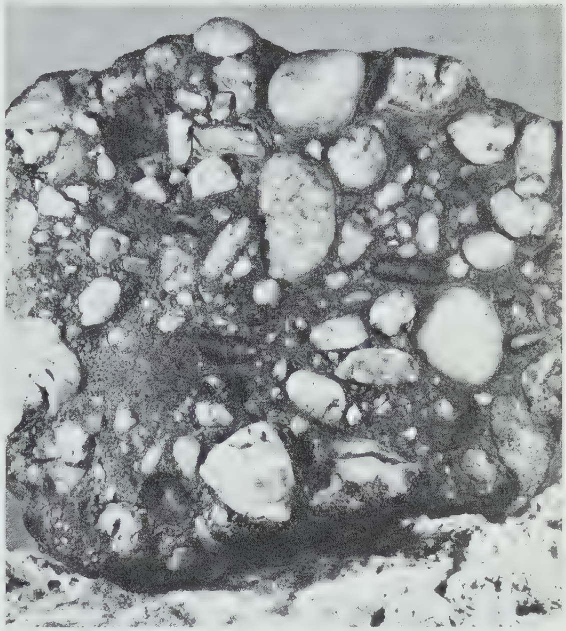
ACTION *Carefully examine the materials in the rock in Figure 16–2a. Can you tell where the sediments that formed it came from? What do the size and shape of the sedimentary particles reveal about the rock in Figure 16–2b? Does one rock consist of sedimentary particles that were probably transported a long distance? Which rock contains fragments that have undergone little erosion and transportation?*

16–2
Layered rocks—pages of earth history

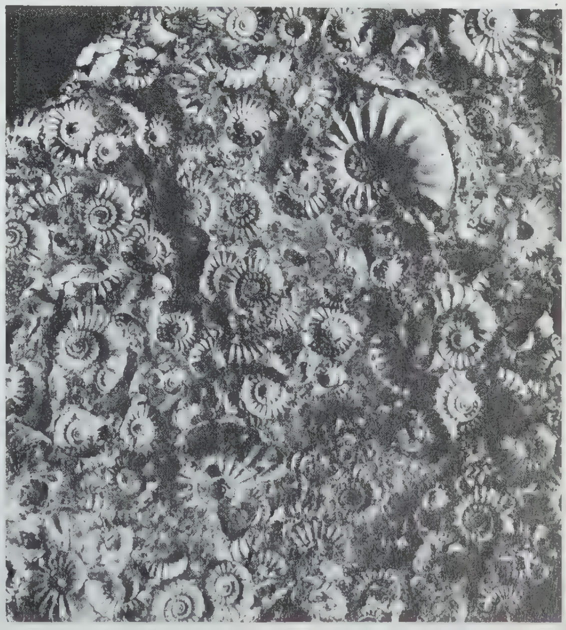
The most common feature of sedimentary rocks is **layering**. (See Figure 16–3.) Each layer or bed of rock gives clues to the conditions

FIGURE 16–2
Where did each of these rocks probably originate?

a.



b.



under which it was originally deposited as sediments. Many layers contain clues that reveal how—and perhaps when—they were formed. Figure 16–4a shows how sediments might accumulate in still water. Currents are present in most bodies of water, including lakes and oceans. Thus, most sedimentary particles settle under conditions shown in Figure 16–4b–d. (Which particles have greater potential energy, the ones that settle on top of the small humps or those that settle in between?)

The layers of sediment are typically deposited in a horizontal position. Tilted rock layers (as in Figure 16–1a) show that the rocks have been

FIGURE 16–3
What causes the layers to show up in these sedimentary rocks?

disturbed since they formed. Tilting provides additional clues to the geologic history of an area.

Interfaces between layers of sediment can be sharp or gradual. (The interfaces are also called **bedding planes.**) One can observe interfaces forming between layers when the conditions of deposition change. What changes would you expect to find in a sediment layer if the velocity of a depositing current suddenly decreased?

Suppose that a stream that deposits large amounts of sand in a basin suddenly dries up. After that stream stops flowing, another stream from a new area begins to empty into the basin. It deposits sand with different characteristics. The bedding plane between the different layers of sand would be distinct. At times, however, changes in the type of sediments take place slowly. Slow changes cause gradual interfaces that are not always easy to recognize.

A single layer of sediment that covers several square kilometers may vary from one place to another. In one place the single layer may be sandy and in other places like gravel or clay. In Figure 16–5 the large sand particles are laid down close to shore, and the particle size gradually decreases to clay away from shore. Notice the places where the clay extends into several of the sand layers. What might this indicate about conditions during deposition?

Many sediments are deposited on the bottoms of streams, lakes, and oceans. You can see grains of sand being moved about by water in streams or in the ocean. Sea shells have been

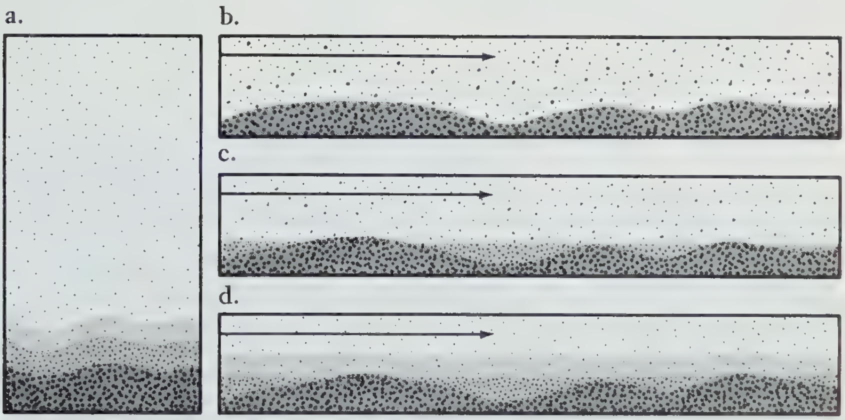
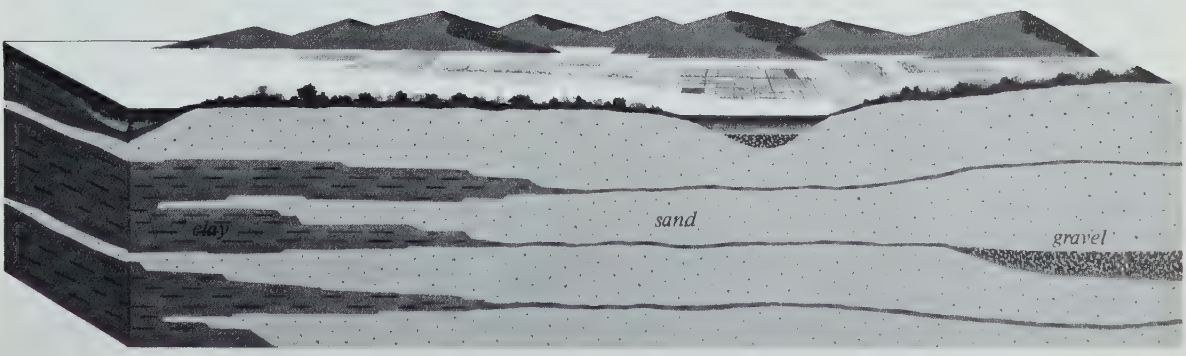


Figure 16–4
Compare the settling of particles in
a. *still water and*
b.–d. *moving water.*

Figure 16–5
Horizontal variation in marine sediments.



found preserved in sedimentary rocks in central Kansas, on the tops of mountains in New England, and in a desert in California. You can be certain that these rocks formed from sediment deposited in an ancient ocean. Other sedimentary rocks appear to have formed on land. If you find the remains of a fossil horse in a sedimentary rock, it is likely that the rock formed on the land.

Deposits of loose sand can be packed and cemented together to form solid rock. So can soil. The cement that holds the sediments together usually comes from other rocks. Ground water that flows through the pores of rocks contains ions of calcium, silicon, and iron. These ions can combine with oxygen and other elements in the water to form a cement of calcite ($CaCO_3$), quartz (SiO_2), or various iron minerals.

Not all layered rocks are sedimentary. There are thick piles of layered lava on the Columbia Plateau in the northwestern United States. (See Figure 16–6.) Layers also form on the sides of volcanic cones when flows of lava pour down the sides and harden. If ashes and dust are blasted from the crater, they may also settle in layers on the cone. Because they are composed of igneous rocks, layers of lava and volcanic debris can usually be easily distinguished from sedimentary rocks.

A volcanic flow may include different-colored layers that are wrinkled like an untidy tablecloth. Rocks within lava flows may contain long crystals that line up in the direction of flow, like logs floating in a river. The arrangement of these crystals can be used to determine the source of the lava. Lava flows may also develop surfaces that look like waves on water. How

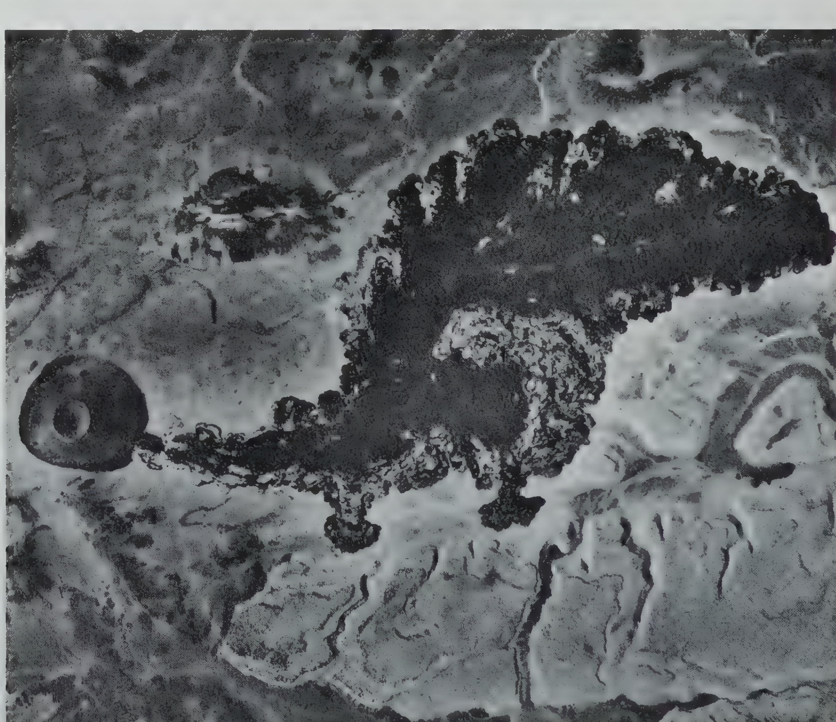


FIGURE 16–6
A recent lava flow adds a new layer to an old lava field.

could these waves, plus the way the crystals are arranged, help determine the origin and direction of the flow? (See Figure 16–7.)

Certain metamorphic rocks also exhibit layering and resemble sedimentary rocks. The layering in these rocks was usually present in the original rock. However, it could also be caused by the metamorphic process or by weathering.

16–3
Cross-beds and ripple marks

Before you can determine the history of most layered rocks, you must be able to tell the bottoms of the layers from the tops. In many areas, rock layers have been tilted or even turned upside down. Fortunately, these rocks may contain clues to the upper surface of the bedding plane. (See Figure 16–8.)

Some sedimentary layers contain cross-beds. Cross-beds are thin layers that lie at an angle to the larger layer that contains them. They are shown in Figure 16–9. One way that cross-beds form in sediments is shown in Figure 16–10. Try to reconstruct the series of events repre-

FIGURE 16–8
Layers of sediment show a gradation in the size of the particles. Is this sketch right side up or upside down?

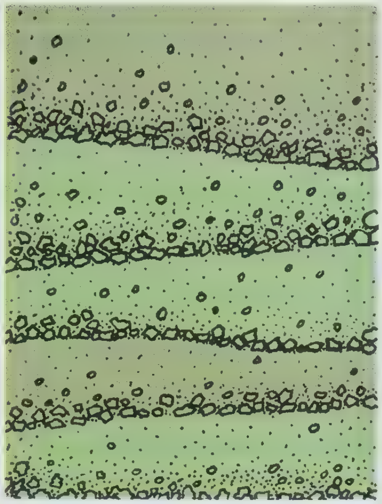


FIGURE 16–9
Cross-bedded sandstone in Zion National Park.

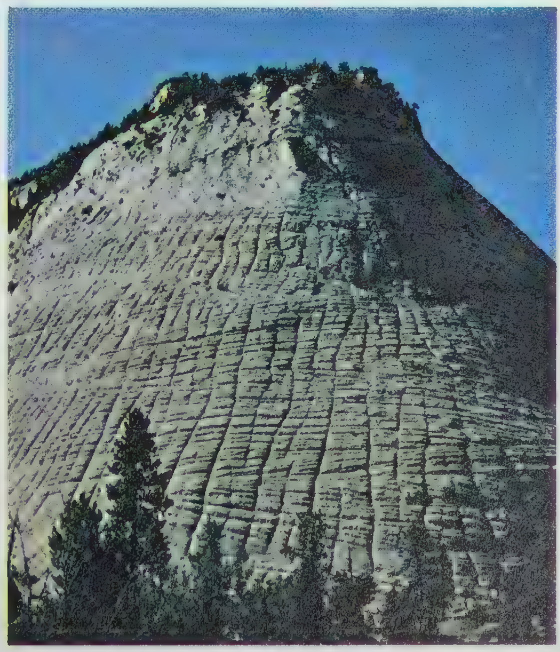
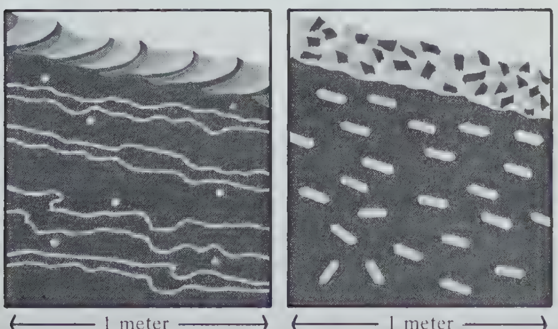


FIGURE 16–7
In what direction did the lava flow in these diagrams?



sented in Figure 16–10. From the shapes of cross-beds shown in the diagram, how could you use the cross-beds to tell the top layer from the bottom? Would they reveal the direction of the current at the time of deposition?

Ripple marks are another feature found in sedimentary rocks. You may have seen them formed by currents in the shallow waters of a lake or ocean. Ripple marks may also be found on sand dunes, on the bottoms of streams, on snowdrifts, or even in puddles after a rainstorm. Ripple marks that are formed by currents moving in one direction have a definite shape. The down-current side of ripple marks is steeper. (See Figure 16–11.)

Symmetrical ripple marks may develop when water moves back and forth. The crests of the symmetrical ripple marks point upward, so they can be used to tell whether a layer has been overturned.

Fossils can also be used to determine whether a rock layer is upside down. When empty clam shells come to rest on a beach, waves or currents usually turn them over so that the hollow side is down. (See Figure 16–12.) Another clue to whether layers have been overturned is the relative ages of the fossils in them.

Action *Place a small tray of wet mud beside a radiator, in a sunny window, or under a heat lamp for several days. Examine the cracks that form on the surface. Imagine similar cracks on a mud layer that has been changed to rock. How could you use these cracks to recognize the top of the layer?*

Figure 16–10
Cross-bedded sediments form when deposition and erosion take turns.

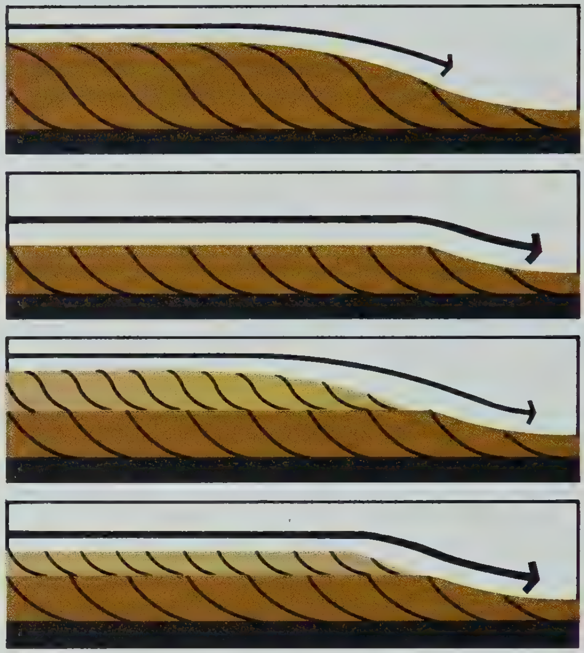


Figure 16–11
Asymmetrical ripple marks. In which direction did the current flow?

16–4
Investigating an ancient stream channel

Suppose that you are a geologist who has found ripple-marked, cross-bedded sandstone exposed at the surface. You suspect that the sandstone was deposited by an ancient stream. Your problem is to trace the channel of the ancient stream.

Procedure

Assume that you have already done the fieldwork for this problem. The map you have prepared (Figure 16–13) shows where you measured the thickness of the rocks beneath the surface. This was done with drill holes. To the left of each location marker is a number in parentheses. It gives the thickness in meters of the sandstone that looks as though it might have been deposited by an ancient stream. Note that at many locations no sandstone was found. The arrows represent the direction of flow in the ancient stream as determined by cross-beds and ripple marks.

Figure 16–12
Symmetrical ripple marks. Is either of these examples upside down?

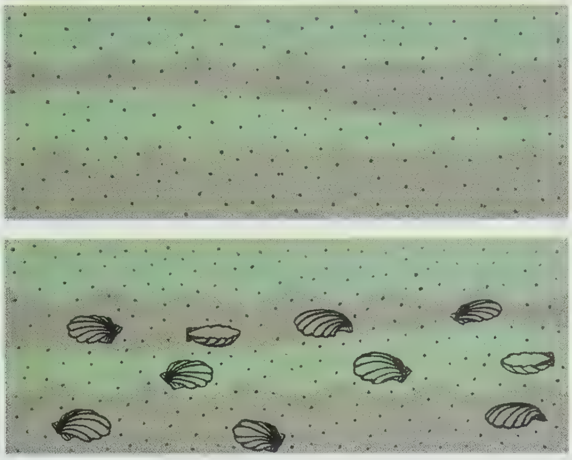
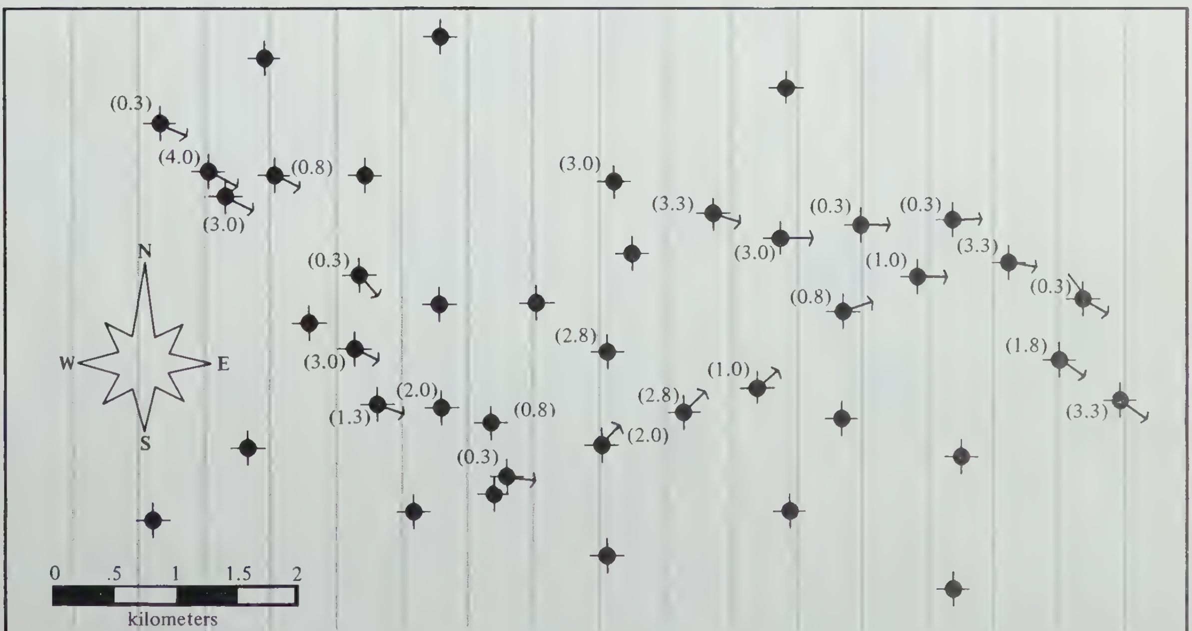


Figure 16–13
Data for investigating an ancient stream channel.



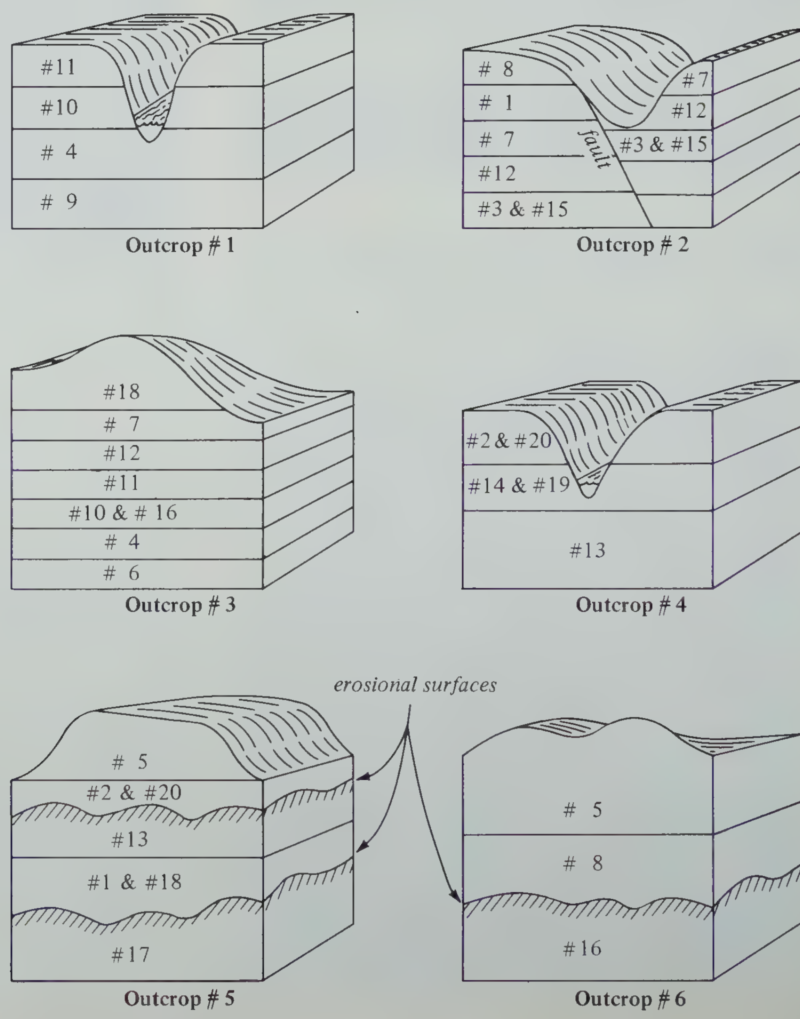
Put a piece of tracing paper or clear plastic over the map and use a soft pencil or crayon to draw the shape of the ancient stream channel. Try to answer these questions:

1. *What evidence can be used to locate the buried stream channel?*
2. *How do you know where to draw the lines showing the ancient stream channel?*
3. *Did the ancient stream meander in loops, or did it flow in a straight line?*
4. *Did the stream have any branches? Can you be certain from the data?*
5. *Make a sketch showing what this sandstone might look like if you could dig a trench five meters deep along one of the gray lines in Figure 16–13.*

Thought and Discussion

1. How do the characteristics of sedimentary rocks help you determine the environmental conditions under which they formed? Give specific examples.
2. Discuss the statement: all layered rocks are sedimentary, and all sedimentary rocks are layered.
3. Describe several ways of determining which is the upper surface of a sedimentary layer.

FIGURE 16–14
Cross sections of six widely scattered rock outcrops.



4. Where would you expect to find the most coarse-grained texture in an igneous intrusion? Why?

Putting the Pieces Together

16–5
Investigating puzzles in the earth's crust

Most of us enjoy putting together the pieces of a jigsaw puzzle. But occasionally pieces of the puzzle are lost, and we find blank spots in the final picture. The clues geologists use to reconstruct earth history are like the pieces of a giant, rocky jigsaw puzzle. In many areas the missing pieces far outnumber those that are available for study. In this investigation you will try to use the occurrence of fossils in rock outcrops to solve a geologic puzzle.

Procedure

Look at the block diagram of the rock layers in Figure 16–14. The numbers in each layer correspond to the particular fossils from Figure 16–15 that are found in that layer. For exam-

Figure 16–15
Fossils found in the outcrops in Figure 16–14.

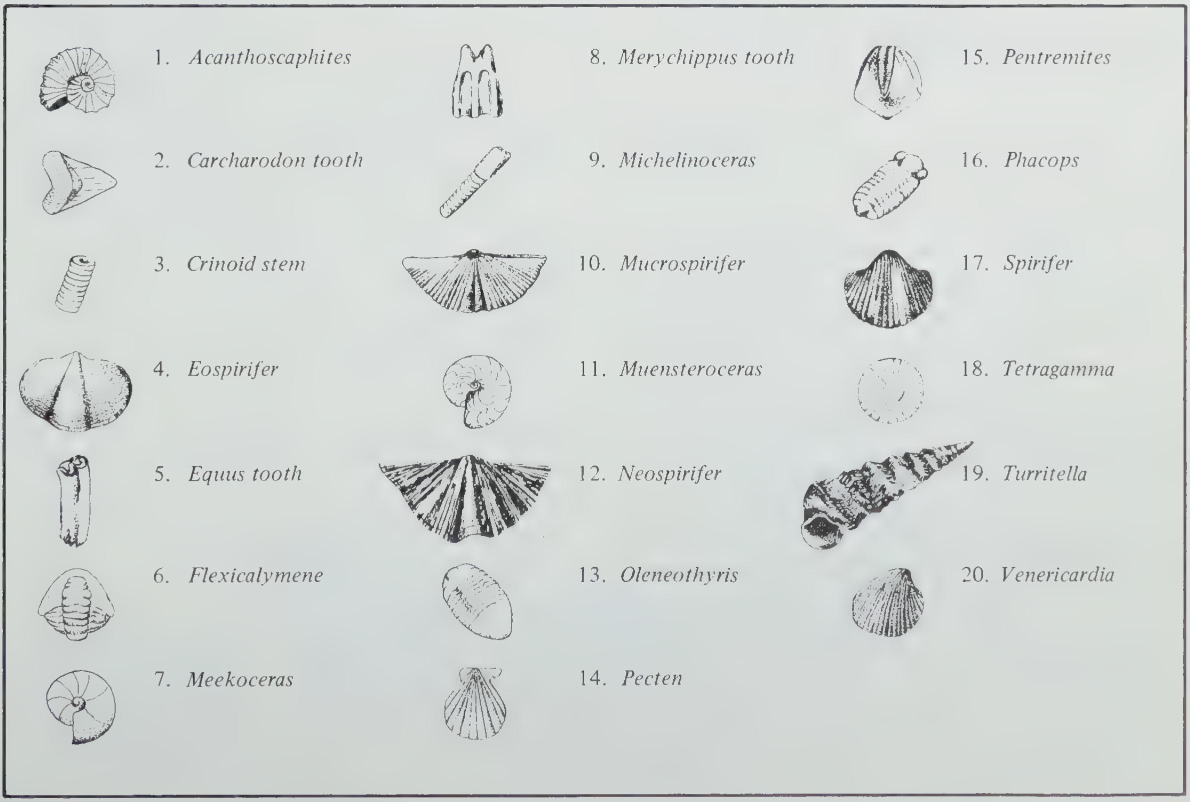
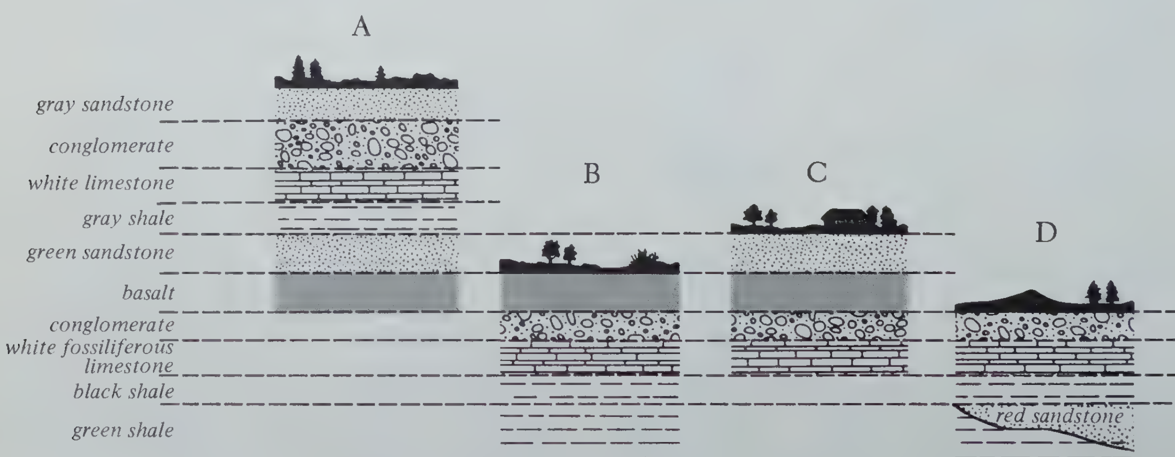


Figure 16–16
Sedimentary layers exposed in the Grand Canyon.

Figure 16–17
Outcrops A and D do not have any rock layers in common. But the rocks in these outcrops can still be correlated.



*ple, if a layer is numbered 10 & 16 then, #10-*Mucrospirifer *and #16-*Phacops *are found in that particular layer.*

Arrange the rock layers in order from youngest to oldest. Be sure to record your reasons for the sequence in which you place them.

1. *Which of the fossils appeared first? How do you know?*
2. *Which of the fossils appeared most recently? How do you know?*
3. *What reason can be given to explain why layers 7 and 12 can be found under 18 and also under 1, but not under the combination of 1 and 18?*
4. *Notice that some fossils such as 10 and 16 can be found together only in some cases. Try to give a reason why.*

16–6
Correlating rock layers

In Investigation 16–5 you matched up, or **correlated,** the layers of rock according to the fossils they contained. Geologists try to correlate rocks to find out which ones were laid down at the same time.

In some places, correlation is simple. Examine the Grand Canyon shown in Figure 16–16. Correlate the different layers exposed in the canyon wall on the left side of the photograph with layers on the right side. Can you see any evidence that the layers on the right and left are the same? Trace several distinct layers across the picture. Would this be more difficult if you were standing down in the canyon rather than up on the rim?

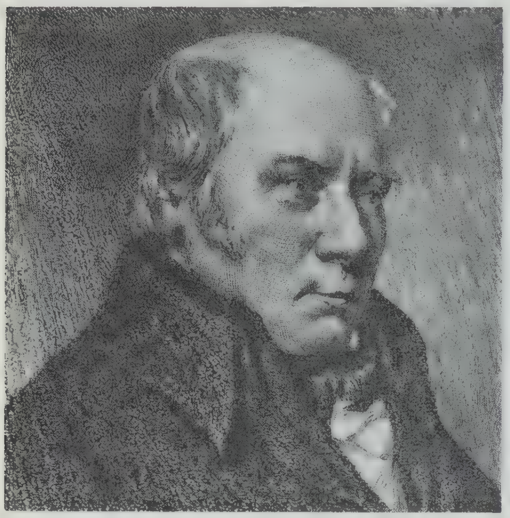
Sedimentary rock layers that have a distinctive color, texture or set of fossils can be easily traced short distances. The farther apart the outcrops, the harder it is to correlate them. Nearly two hundred years ago William Smith discovered that physical characteristics and fossils could be used to correlate rock layers many kilometers apart. This English surveyor's discovery was one of the "kilometerstones" in our understanding of earth history.

An example of a correlation problem is shown in Figure 16–17. The diagram shows rock outcrops in four different places. A geologist looking at these outcrops recognizes several different layers. He wants to know whether the rocks at section A are related to the rocks at section D, which is nine kilometers away. He sees that the white limestone in sections B, C, and D contains fossils and is covered by conglomerate. The conglomerate in turn is covered by basalt. Because the sequence of layers is the same, he correlates the conglomerate layers in the three sections.

He also notices that basalt in sections A and C is covered by green sandstone. So, he correlates section A with section C. He can now tell how sections A and D are related to each other, even though they have no layers in common. The geologist concludes that the red sandstone in section D gradually thins out and does not extend into location B. Is this a reasonable conclusion? Carefully examine the sections for other evidence that might support this correlation.

It is much more difficult to correlate rock layers in widely separated areas, such as on dif-

WILLIAM SMITH



In 1799 a young surveyor named William Smith (1769–1839) was asked to plan the route of a new canal for southern England. Smith knew that the cost of the canal would depend on the types of rock it was dug through. Consequently, he needed to know the geology of the region. There were few trained geologists in those days, so the young engineer had to make his own geological studies. Luckily for Smith, his hobby was collecting rocks and fossils—a pastime that he soon put to practical use in his work.

In digging through the rocks, Smith learned that different rock layers could be identified by the fossils they contained. The young surveyor also noticed that the fossils found in each rock formation were different from fossils in the rocks above and below. Smith recognized these fossils as valuable field guides and used them to plan his excavations.

He also studied fossils that were exposed in the banks of rivers and the walls of quarries. He found that he could use these fossils to predict the location and characteristics of the rocks beneath the surface. William Smith had thus developed the geologic technique of correlation. Matching the rocks and fossils from widely separated areas is one of the most important techniques used to read the record in the rocks. Smith made this important discovery when he was only 22 years old.

A famous story is told of Smith's visit to the Reverend Benjamin Richardson, who collected fossils as a hobby. Smith astonished the minister by telling him exactly where and in what formation specimen after specimen had been found. He then predicted correctly the rock layers and fossils in a distant hill. As a result of his work, "Strata" Smith, as he was later nicknamed, constructed the first geologic map of England, Wales, and part of Scotland.

ferent continents. During the past, conditions in different areas varied just as they do today. Deposition was going on in some places, erosion in others. There are no individual rock layers that span the entire earth or even an entire continent. Nevertheless, earth scientists can correlate rocks in different continents.

One of the best ways to correlate rocks in widely separated areas is by using fossils. For example, similar species of fossils are found in

Africa, France, and North America. Although widely separated, these creatures all lived at the same geologic time. Scientists assume the rocks that contain these fossils consist of sediments deposited during the same part of geologic history.

16–7 Outcrops reveal a sequence of events.

Sedimentary layers are deposited horizontally. Layers may then be deformed by folding, faulting, or erosion. Suppose you conclude from fossils in two different layers of rock that Cretaceous rocks lie directly on top of Cambrian rocks. How can you account for the missing layers?

This situation would be similar to discovering that the middle 100 pages of a detective novel had been torn out. What would you do to find out about the full story? You might be able to guess at the events that occurred in the middle of the book if you had read other detective novels written by the same author. In studying rocks, you might not be able to tell the complete story from a single outcrop. But by correlating the rocks in different outcrops, you might be able to find out what happened during the period of the missing layers.

Where layers are missing from a sequence, the upper surface of the older rocks may be an old erosion surface or unconformity. Unconformities are easily recognized when folded rocks are eroded and flat-lying rocks are deposited on top of them. (See Figure 16–18.)

The geologists must also be able to determine the relative ages of igneous and sedimentary rocks in the same outcrop. Suppose that you found a layer of igneous rock in the middle of

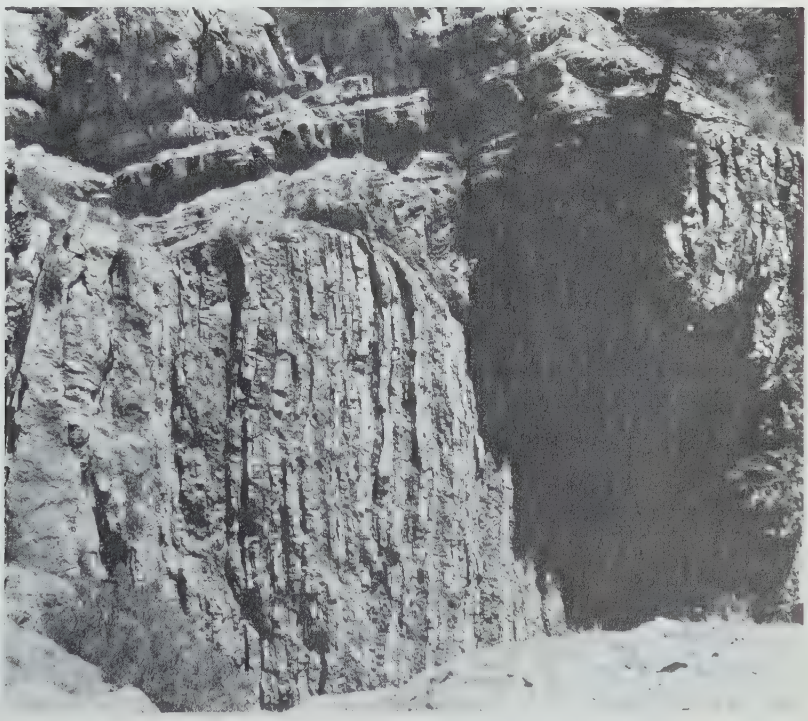


FIGURE 16–18
Find the unconformity in this picture.

Figure 16–19
Which diagram shows an intrusion and which a buried lava flow?

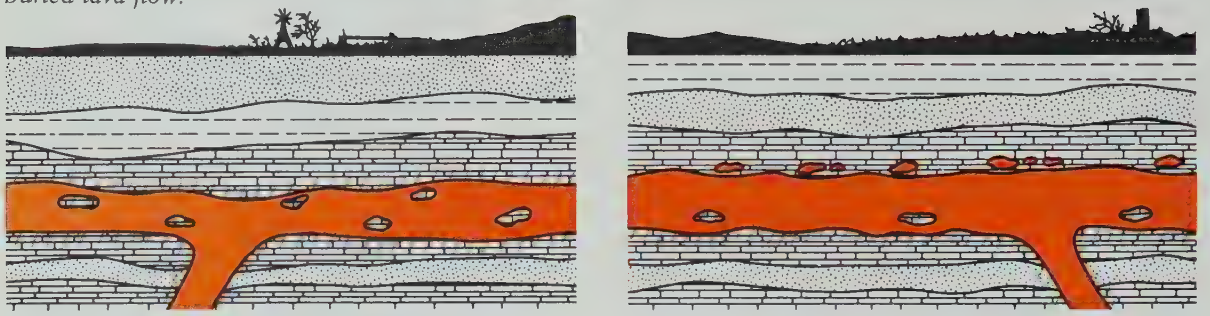
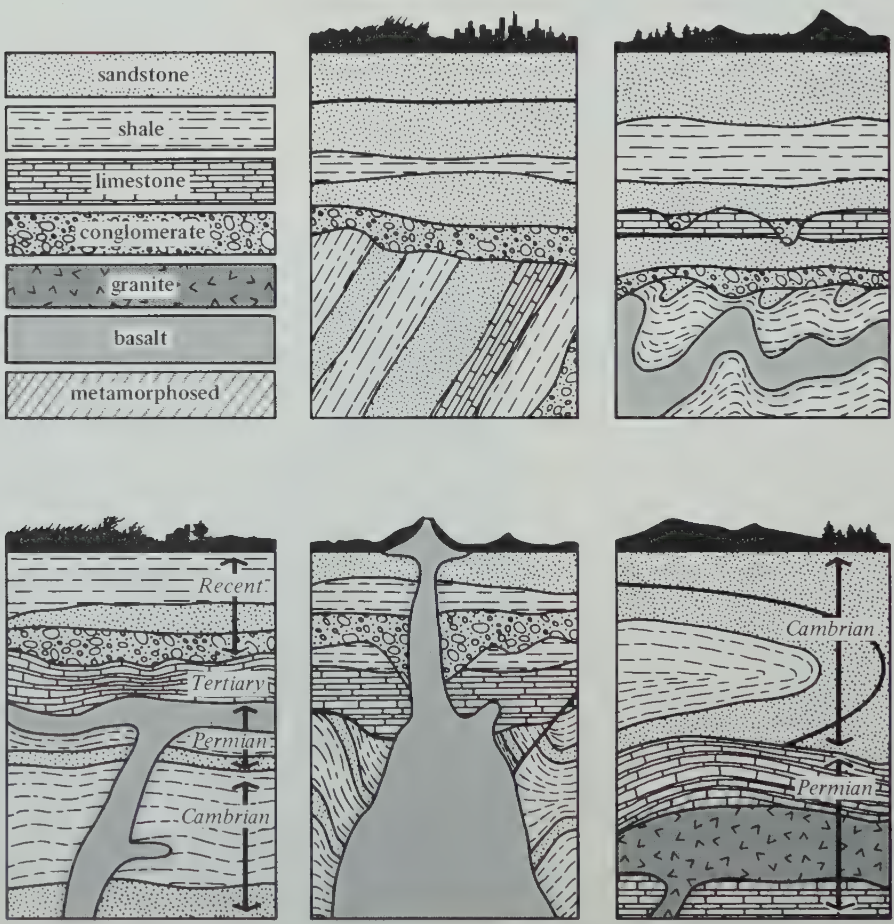


Figure 16–20
Develop a geologic history for each cross section.



a thick pile of sedimentary rocks. Such igneous rock could be a lava flow that was buried by sediments. It might also be an intrusion squeezed in between the layers of sedimentary rocks already deposited. An igneous intrusion will cut through and bake the rocks around it or carry rock fragments along with it.

Examine Figure 16–19 carefully. Can you tell which diagram represents a buried lava flow and which represents an intrusion? What is your evidence? What are the relative ages of the basalt and the top rock layer in each sketch?

Action *A series of additional geologic cross sections is given in Figure 16–20. Examine each of these cross sections and describe the sequence of events that occurred in each area. Begin with the oldest and end with the most recent event.*

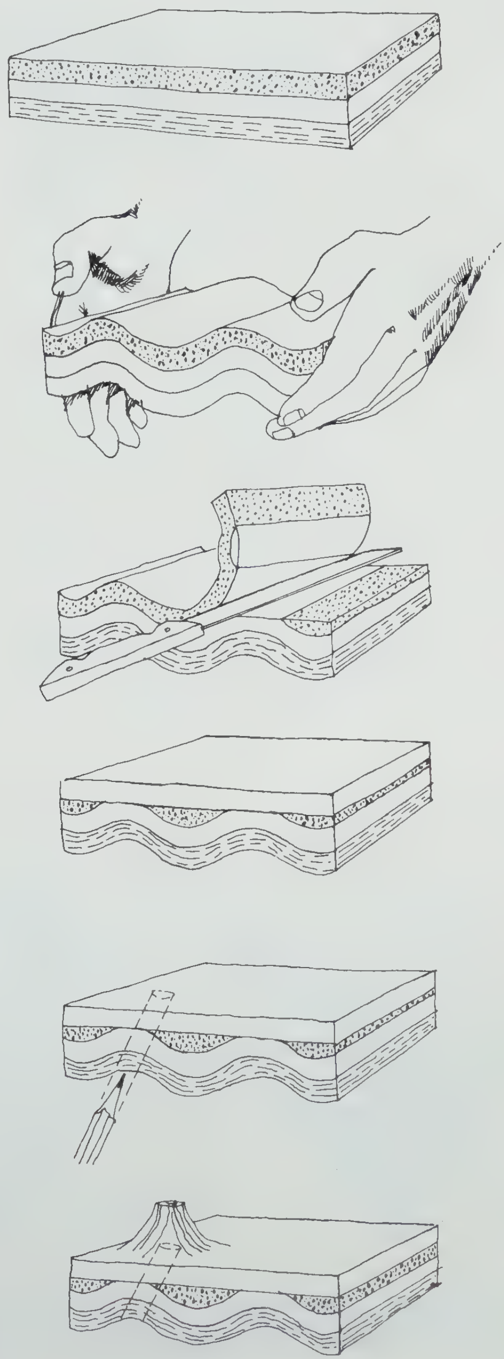
16–8
Interpreting a chapter in earth history

If you examine a rock outcrop carefully, you can usually piece together the sequence of events that formed it. In this investigation you will make and interpret geological models made of clay.

Procedure

Figure 16–21 shows how you can make geological models out of clay. Your group should make up its own outcrop. Be sure to keep a list showing the exact sequence you used to make the model. When the models have been com-

Figure 16–21
One possible sequence of steps in making a geological model.



pleted, exchange them with another group of students in the class. Now try to determine the steps used to construct the new model. The group you exchanged with will do the same with the model you made.

As you examine the model, your group should try to answer these questions:

1. *Which layer is the oldest? How do you know?*
2. *What are the relative ages of the rest of the layers?*
3. *If your model contains folded layers, when did folding occur? Can you determine from the shape of the folds how they were formed?*
4. *Is there evidence that any of the layers have been eroded? How do you recognize a former erosion surface?*
5. *How would you explain a layer of one color cutting through layers of other colors?*
6. *Have any layers been disrupted by faults?*

If you have difficulty answering any of these questions, what additional information do you need to help you interpret the model?

16–9
Clues to ancient climates

Certain rocks contain evidence that climates have radically changed during the past. Rocks that contain fossils are especially helpful indicators of ancient climates.

Living organisms, especially plants, grow best in certain climates. For example, palm trees do not grow in Alaska, nor does reindeer moss grow in the tropics. Fossilized plants and animals probably had the same climatic preferences as their present-day relatives. Fossils of subtropical plants such as magnolias are found in rocks on the Arctic island of Spitsbergen. This suggests that the climate there was once much warmer than it is now.

Some fossil plants have features that suggest they grew in a warm climate. Large cells or a lack of annual growth rings are examples. Dinosaurs were cold-blooded, like the modern day reptiles. Large dinosaurs lived in what is now northern United States and southern Canada. The climate there was probably mild during this time, because reptiles must hibernate when the temperature drops toward freezing. A dinosaur 20 meters long and weighing several tons would have had trouble finding a cave large enough to sleep in during the cold winters.

The number of fossils can also be a clue to an ancient climate. More species of plants grow in the tropics than in the higher latitudes. The situation was probably the same in the past. Therefore, finding a large variety of fossil plants is good evidence that an area once had a tropical climate.

You can study the world-wide distribution of certain fossils during a single geologic period. You may then discover that each species is restricted to a latitudinal zone. This indicates that it could only live under particular climatic conditions. The maps in Figure 16–22 describe probable climatic zones from several different periods. The map on the left shows a subtropical zone. Rocks have been found there containing fossils whose modern relatives live in sub-

tropical areas. Do you think that such maps would be reliable for much earlier periods?

Reef-building corals are especially useful for identifying ancient environmental conditions. Most present-day species need warm water to digest their food and to carry on other life processes. Corals live only in salt water and prefer temperatures between 25 and 29°C. In addition, most corals prefer depths of less than 75 meters.

Other organisms also provide clues to environmental conditions. For example, some fish require fresh water and would die if sea water invaded their habitat.

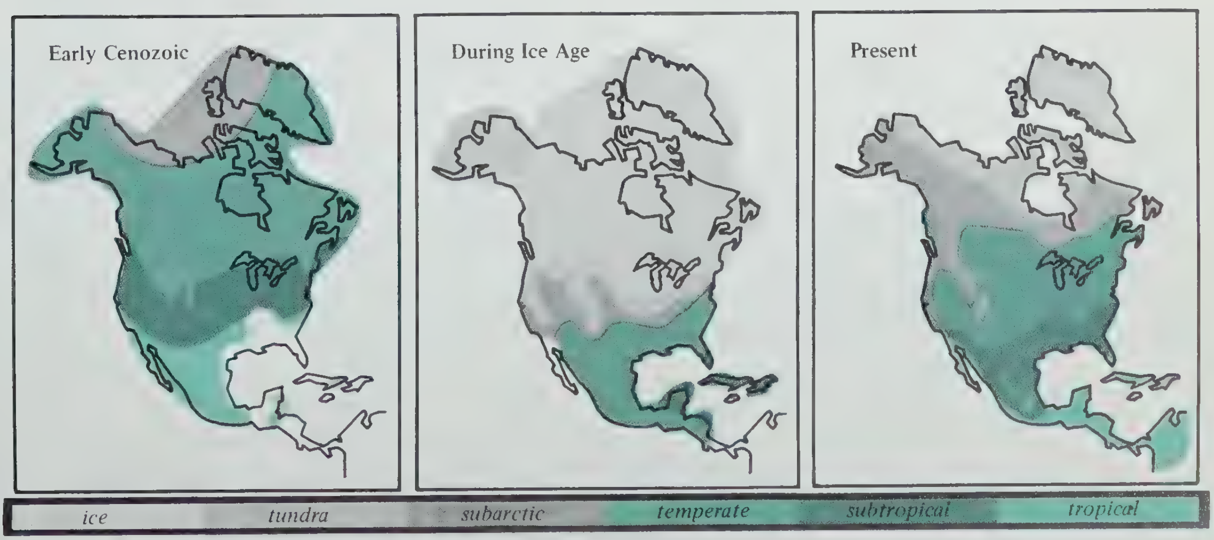
Minerals can also indicate ancient climates. Gypsum ($CaSO_4 \cdot 2H_2O$) and rock salt ($NaCl$) are examples of such minerals. When there is net evaporation of water from lakes or soil, salts may crystallize and form layers. Salt layers formed this way are now being mined in Michigan, Kansas, and Germany. How would these salt deposits indicate climates for those areas during ancient times?

ACTION *Imagine that you have been transported several million years into the future. What might you find in the rock record representing the 1970's in the area where you now live? What objects might survive? Which ones might not? What could a future geologist learn about our civilization from common objects?*

Thought and Discussion

1. How could you recognize a buried erosion surface?
2. How could you tell whether an igneous rock was from a lava flow or an intrusion?

FIGURE 16–22
Climatic changes have occurred in North and Central America since early Cenozoic time.



3. What types of evidence about ancient climates are found in rocks?
4. How are fossils used in correlating rocks separated by great distances?

Unsolved Problems

Many areas of the earth's surface have not been carefully examined, and some parts have not been studied at all. As a result, our knowledge of earth history is far from complete. Even areas that have been studied in great detail provide new information when improved techniques are used to study them. The geologic history of your area probably has large gaps in it, too, and some of these gaps may never be filled. Find out what you can about your local geology and determine how much information is missing from the geologic record.

Are sedimentary, igneous, or metamorphic rocks forming or eroding in your area right now? You might contact local conservation groups, travel to mines, quarries, or deep road cuts to collect your information.

Chapter Review

Summary

Rocks reveal many things about past events on the earth. The layering in sedimentary rocks can show the conditions under which the rocks formed and the types of sediment involved. Fossils may reveal whether sedimentary rocks originated in the ocean or on land. Layering in igneous and metamorphic rocks may also provide clues to the conditions of their origin.

Sedimentary rocks, cross-beds, and ripple marks help geologists distinguish the tops of layers and the direction of the current. The position of fossils and mineral crystals also show if layers have tilted or been overturned.

The texture and mineral content of rocks are important clues to their origin. Rounded or coarse particles, shell fragments, and trace minerals in sedimentary rocks all provide information. The texture of igneous rocks reveals how fast they cooled. Crystal sizes in metamorphic rocks depend on the temperature and pressure during formation.

Rocks in different outcrops can be correlated. The types of rocks and their fossils can tell whether they are related. Correlation helps fill in missing parts of the geologic record. Certain layers missing from the sequence at one location may be found at another location. Buried erosion surfaces often account for the missing layers.

The relative ages of rocks that cut through each other can also be determined. For example, igneous rocks that have baked surrounding sedimentary rock and that contain sedimentary fragments are usually younger intrusions.

Rocks may be useful in revealing ancient climates. Fossils of tropical plants and animals have been found in areas that are now arctic or subarctic. They show that the climate in these regions was once much warmer. There are abundant deposits of minerals such as salt or gypsum in some temperate areas of the world. They probably formed at a time when these areas had different climates.

Questions and Problems

A

1. In section 16–2 there are examples of a single layer of sediment varying from one place to another. Describe some other circumstances in which horizontal variation might occur within a body of rock.
2. How would you explain a graded bed with large grains on top and smaller grains on the bottom?
3. How could a sandstone form that is composed almost entirely of well-rounded sand grains?
4. What features do sedimentary rocks have that igneous and metamorphic rocks don't?
5. Suppose you find two sedimentary rocks. One of these, composed of rounded fragments of calcite, is relatively soft. The other rock, composed of fairly angular fragments of quartz, is relatively hard. Can you say whether the calcite grains have been transported farther than the quartz grains?

B

1. Under what conditions might sediments not be horizontal at the time of deposition?
2. Are the interfaces between sedimentary layers always distinct and abrupt? Explain your answer.
3. Would you expect to find horizontal variation in igneous and metamorphic rocks?
4. Quartz is probably the most common mineral in sandstones throughout the world. Yet on many beaches in Florida most sand grains are composed of calcite. Suggest reasons for this situation.
5. Some rocks consist entirely of volcanic ash and fragments of rock that have fallen into a pile at the foot of a volcano. Would rock formed from this material be sedimentary or igneous?

C

1. Suggest a way that cross-beds might form from ripples in sand on the bottom of a sedimentary basin.
2. Suppose you find a rock composed of 50 per cent fragments and 50 per cent crystalline cement. Would you call it fragmental or crystalline?

Suggested Readings

Barnett, Lincoln and the editors of *Life*, *The World We Live In*. Silver Burdett, Company, Morristown, N.J., 1955, especially pages 58 and 59.

Matthews, William H., III, *Introducing the Earth—Geology, Environment, and Man*. Dodd, Mead and Company, New York, 1972, Chapters 5 and 13.

Page, Lou W., *The Earth and Its Story*. American Education Publications, Columbus, Ohio, 1961, Chapters 14 and 15. (Paperback)

Wycoff, Jerome, *The Story of Geology*. Golden Press, New York, 1960, pp. 24–29 and pp. 166–175.

17. Life: Present, Past, and Future

In 1900 a Russian hunter was slowly making his way along the Berezovka River in Siberia. He was tracking a wounded deer but found something quite different. Imagine the hunter's surprise when he found what appeared to be the head of a full-grown elephant in the frozen ground. The discovery of this well-preserved beast caused great excitement. It was found 100 kilometers inside the Arctic Circle, more than 3,250 kilometers north of where elephants live today.

News of the discovery eventually reached scientists in Saint Petersburg (now Leningrad). An expedition was sent to collect the unusual specimen. Although part of the flesh had been eaten by wild animals and the body was badly decayed, it soon became apparent that this was no ordinary elephant. The creature shown on the opposite page had very long curved tusks, and its body was covered with thick hair. Beneath the coarse hair was a protective undercoat of woolly fur.

The hunter had found the frozen carcass of a woolly mammoth, an extinct elephant-like creature that inhabited Eurasia and North America many thousands of years ago. Since the discovery of the Berezovka mammoth, similar frozen fossils have been found in Siberia and Alaska. We know that elephants do not now inhabit Siberia and Alaska. These remarkable fossils are reminders of a time when the Arctic region supported life forms entirely different from the ones in that area today.

You have already learned that fossils are clues to the nature of ancient climates. Equally important, fossils provide valuable information about the development of life on earth. The

earth scientist is especially interested in the interaction between the world of living things and the atmosphere, the hydrosphere, and the lithosphere.

Life Today

17–1
What is life?

Untold billions of organisms inhabit the earth. They live on the land and in the waters. Microscopic organisms even fill the air that you breathe. Organisms range in size from microscopic plants and animals to the giant sequoia trees of California and the great whales of the oceans. There is hardly a place on earth where life in some form does not exist. But despite the variety and abundance of living forms, **life** is a most difficult term to define.

ACTION *Consider a frog on a rock and a plant. What differences between the animal and the rock in Figure 17–1 determine which is alive? How are the plant and the frog similar? How are they different? How are the plant and the rock similar? How are they different? Was the rock ever alive? Could the rock show any evidence of life?*

The chemical make up of living things is different from that of non-living things. The members of the **biosphere**, the living world, consist mostly of organic compounds. These are compounds containing carbon atoms that join with one another and with atoms of other elements. The amount of carbon in living things might suggest that it is one of the more common elements in the earth's crust. Figure 2–25 showed that oxygen and silicon are the most abundant elements by weight. Carbon ranks seventeenth in order of abundance because crustal rocks contain less than one-tenth of a per cent of carbon by weight.

A few non-living or inorganic compounds may be produced by plants and animals. Many animals such as clams, snails, and oysters build shells of calcite ($CaCO_3$). Others, like certain sponges, have hard parts composed of silica (SiO_2). However, most inorganic substances are not produced by living things.

Scientists have named more than a million species of plants and animals, and new species

FIGURE 17–1
Which of these things are alive? How are living things and inanimate objects different?

are continually being described. A **species** is a group of organisms that can produce fertile offspring. About 130,000 of the catalogued species are now no longer in existence. Most of these extinct species disappeared during earlier chapters in earth history. Some of them have been eliminated more recently by the careless actions of man. Four billion species of plants and animals may have lived during the past 600 million years.

Life is widespread because certain species can adapt to almost any environment on earth. Bacteria have been found in the upper regions of the atmosphere more than 20 kilometers above the earth's surface. They have also been found in water taken from oil wells nearly 2 kilometers deep. Certain specialized organisms are active at $-4°C$ in polar oceans and others live at 85°C in hot springs. Some organisms thrive in deserts, some in the acid water of peat bogs, and some even in Great Salt Lake.

There are few regions on earth that do not support some form of life. Organisms are especially abundant at interfaces. The plant-soil zone is a typical interface environment for life. The greatest concentration of organisms is found in the 200 meter deep zone that lies just beneath the surface of the oceans. This is the zone reached by sunlight, the energy necessary for plant growth. Here, too, live most of the world's animals. Most of these plants and animals are microscopic and consist of single cells.

In the shallows, the ocean-sea floor interface is especially rich in animal life. Creatures there swim over, crawl on, or burrow into the bottom sediments. Others are attached to the ocean floor.

17–2
Life and energy cannot be separated.

All life functions require activity, and activity requires energy. Life on earth has always depended on energy from the sun. This energy comes to the earth as light. Green plants can capture light energy because they have chlorophyll. They can make new chemical compounds by trapping light energy during the process of **photosynthesis.**

Photosynthesis means "combining by means of light." Water and carbon dioxide combine to form carbohydrates. **Carbohydrates** are organic compounds of carbon, hydrogen, and oxygen. Sugars, starches, and cellulose are common carbohydrates. The chemical reaction in photosynthesis can be written in the following way:

$$6CO_2 + 6H_2O \xrightarrow[\text{chlorophyll}]{\text{light energy}} C_6H_{12}O_6 + 6O_2$$

(When chlorophyll is present, light energy turns carbon dioxide and water into carbohydrates and oxygen.)

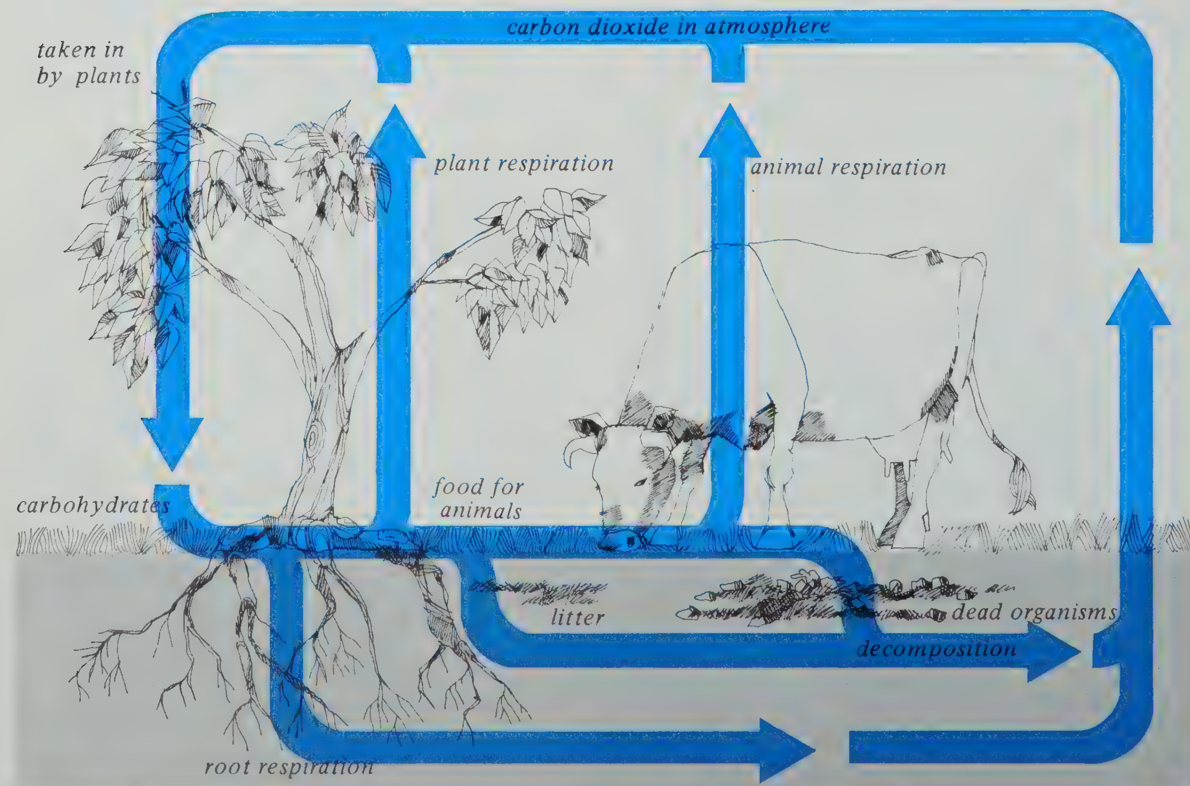
Photosynthesis changes light energy into a form living things can use. The light energy is changed to chemical energy stored in the carbohydrate molecule. It can then be used by plant and animal cells to provide the energy necessary for life functions. Only plants can convert light energy to the usable chemical energy of food. Thus, animals depend on plants for their survival.

Consider a typical green plant such as grass as the beginning of a **food chain.** During photosynthesis the grass converts light energy into chemical energy. When the grass is eaten by a deer, its energy is then transferred to the deer. Suppose the deer is killed and eaten by a mountain lion. The energy obtained by the deer from the grass is then transferred to the mountain lion. The lion will probably not eat all of the deer's body. Some of it will rot and provide energy for organisms called **decomposers.** The decomposers further break down the remains of the deer (and eventually the mountain lion) into a form usable by plants. This series of plants and animals make up a food chain. Food chains transfer energy from one part of the biosphere to another.

17–3 Organisms and chemical cycles

Chemical elements can move through a cycle from non-living to living objects and back again.

FIGURE 17–2
The carbon cycle. What different pathways could one carbon atom follow to go from the atmosphere, to living organisms, and back again?



An example is the **carbon cycle** (Figure 17–2). The main pathway in the carbon cycle is from the atmosphere into living things and then back again. Living organisms discard carbon-bearing wastes that are returned to the land, air, and water. When living things die, carbon compounds are left in their bodies. The remains of each dead plant or animal are food for decomposers. The decomposers release carbon to the atmosphere as carbon dioxide. In this way, decomposers make materials available for reuse by plants. Most decomposers are microscopic. Some, like the toadstool, are much larger.

In some instances carbon may stray from this main path; for example, certain organisms take carbon into their shells as $CaCO_3$. When these animals die, the shells are not broken down by decomposers but may be deposited as sediment.

Large masses of carbon compounds piled up in the earth have been changed to coal or petroleum. Coal is mostly plant remains that have been enriched in carbon by the removal of other elements. Petroleum's origin is not clearly understood. Perhaps decomposers changed the remains of microscopic plants and animals into crude oil. Petroleum and coal are commonly called **fossil fuels** because they are the remains of ancient plants and animals. Fossil fuels are a stockpile of solar energy made long ago.

The water cycle is also basic to life. Without the continuous return of fresh water to the land through rain and snow, the land would soon become a lifeless desert. Water forms an important part of all living things. Organisms that live on the land may pick up water at a number of points in the water cycle. Land plants usually absorb water from the soil, while land animals drink it. The amount of water in different organisms varies. Our bodies are about 66 per cent water. A jellyfish may be more than 95 per cent water.

Moisture absorbed by plants is carried to the leaves. Most of it evaporates through openings in the leaves. Animals return moisture to the atmosphere through respiration, perspiration, and waste products.

Thought and Discussion

1. Where do organisms get their energy?
2. Give your own definition of life.
3. Can you explain the statement: Coal is "petrified sunshine"?
4. Explain how the idea of cycles is useful in relating natural processes.

Life of the Past

17–4
Fossil evidence of prehistoric organisms

In Chapter 16 you saw that the history of the earth can be unraveled from evidence found in the rocks. Certain rocks in Utah have fossil evidence that dinosaurs once lived there. According to fossil evidence great swampy forests once covered parts of Pennsylvania and Illinois. Scientists who do the detective work with this kind of fossil evidence are called **paleontologists.** They use fossils to trace the development of life and to reconstruct the geologic past.

To comprehend organisms that vanished

from the earth hundreds of millions of years ago, the paleontologist must know as much as possible about living species. The environment of extinct organisms is not always known. When a group of fossil organisms closely resembles a living group, we can usually assume that the two groups lived under similar conditions. Thus, the principle of uniformitarianism is again applied to interpreting the past. The present is a key to the past.

The term "fossil" comes from the Latin word *fossilis*, meaning "dug up." But most fossils are not dug from the ground. They are uncovered by weathering and erosion (Figure 17–3). Like living organisms, fossil plants and animals are numerous and varied. Animal fossils range in size from dinosaur bones more than two meters long and weighing several hundred kilograms to fossils so tiny that hundreds of them would fit on the head of a pin! These smaller forms are called **microfossils** because they must be studied with a microscope (Figure 17–4).

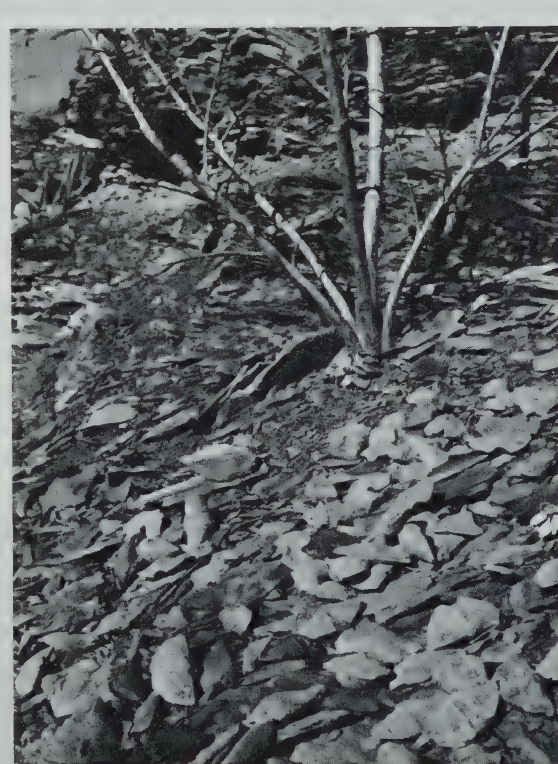
Plant microfossils are abundant in certain types of rocks. For example, thousands of tiny one-celled plants may be found in a single teaspoonful of some crushed marine sedimentary rock (Figure 17–5). Plant fossils are not as common as animal fossils. Why do you think fossil plants are less common than fossil animal remains?

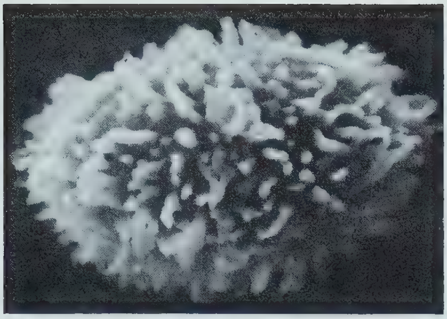
The great stone trees that lie scattered about Petrified Forest National Park in Arizona (Figure 17–6) are spectacular examples of fossil plants. The Petrified Forest tells a lot about the geologic history of this area of Arizona. Leaves, seeds, and even the fruit of prehistoric plants have been preserved.

ACTION *If you live in an area where rocks containing fossils are exposed, take a field trip and make a collection of fossils. Visiting a nearby museum or reading several of the books listed in the Suggested Readings at the end of this chapter will give you some ideas about the collection, identification, and display of fossils. The ESCP pamphlet,* Field Guide to Fossils, *will also help you plan your field trip.*

Some fossils represent the actual remains of plants and animals such as bones, teeth, leaves, and shells. Other fossils are simply traces such as trails left by worms, the imprints of leaves, and the tracks of dinosaurs. (See Figure 17–7.)

FIGURE 17–3
Brachiopods weathering from a rock outcrop.





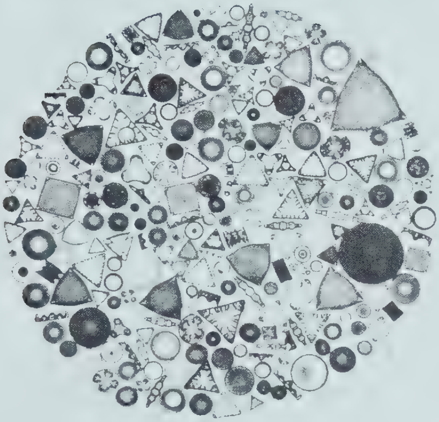


Figure 17–4
(*top left*) *This fossil fern spore is approximately 7,000 years old. The magnification is 1000 X.*

Figure 17–5
(*left*) *Fossil diatoms, microscopic plants.*

Figure 17–6
(*top right*) *These fossils are the remains of trees that lived about 200 million years ago.*

Figure 17–7
(*right*) *Approximately how old are these dinosaur tracks?*

Some trace fossils provide almost as much information as actual organic remains. What could you learn about a dinosaur from its tracks?

17–5
Investigating a footprint puzzle

Suppose you discovered a set of fossilized tracks like those in Figure 17–8. If you wanted to reconstruct what had happened, your problem would be similar to a detective's. You would have to determine past events from limited evidence. The only clues would be the footprints preserved in stone.

FIGURE 17–8

PROCEDURE

Look at Figure 17–8. These tracks are common in certain parts of New England and in the southwestern United States.

1. *Can you tell anything about the size or nature of the animals from their footprints?*
2. *Were all the tracks made at the same time?*
3. *How many animals were involved?*
4. *Did the animals walk on four legs or were they two-legged creatures?*
5. *See if you can reconstruct the series of events represented by this set of fossil tracks. Your teacher will show you two more parts of this footprint puzzle.*

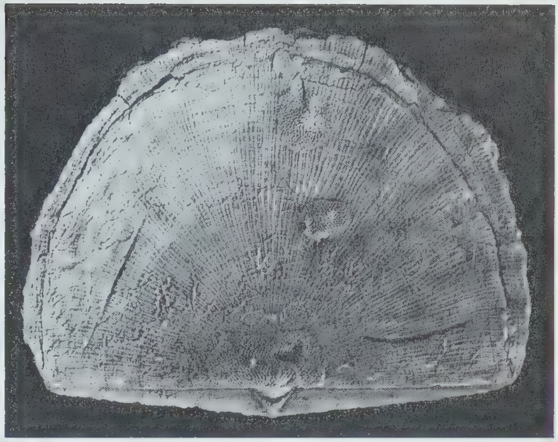
17–6
How fossils form

Dead plants and animals decay rapidly. Only hard parts such as teeth, shell, and wood are normally fossilized. However, under favorable conditions, organisms composed completely of soft parts, such as jellyfish, have been wholly preserved (Figure 17–9).

Even an organism with hard parts will not necessarily be fossilized. You know that you rarely see the complete skeleton of a dead animal. It is also hard to find a seashell on the beach that is not broken or badly worn. There are many ways that the remains of organisms are destroyed. When an animal dies, its flesh is immediately attacked by a variety of organisms ranging from vultures and coyotes to maggots and bacteria. The flesh soon disappears, leaving only bones, teeth, or shell. These may also be

a.

b.



c.

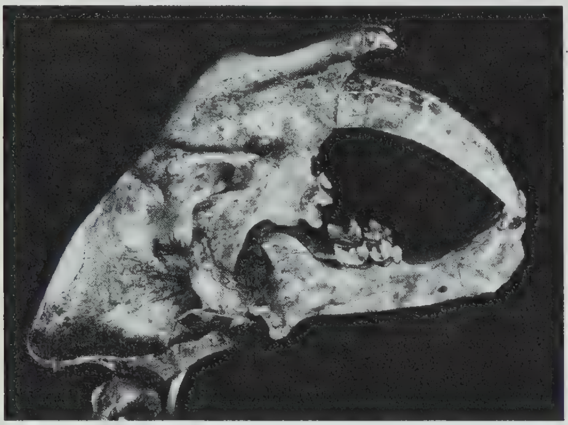
d.

e.

FIGURE 17–9
Some typical invertebrate fossils.
a. *jellyfish*
b. *brachiopod*
c. *arthropod*
d. *echinoderm*
e. *rugose coral*

a.

b.



c.

d.

FIGURE 17–10
Some typical vertebrate fossils.
a. *a young* Ichthyosaurus
b. *skull of a saber-toothed cat*
c. *shark's tooth*
d. *a horned dinosaur* (Triceratops)

destroyed. Some shells and bones are crushed by overlying sediments. Others are eroded as they tumble along a stream bed.

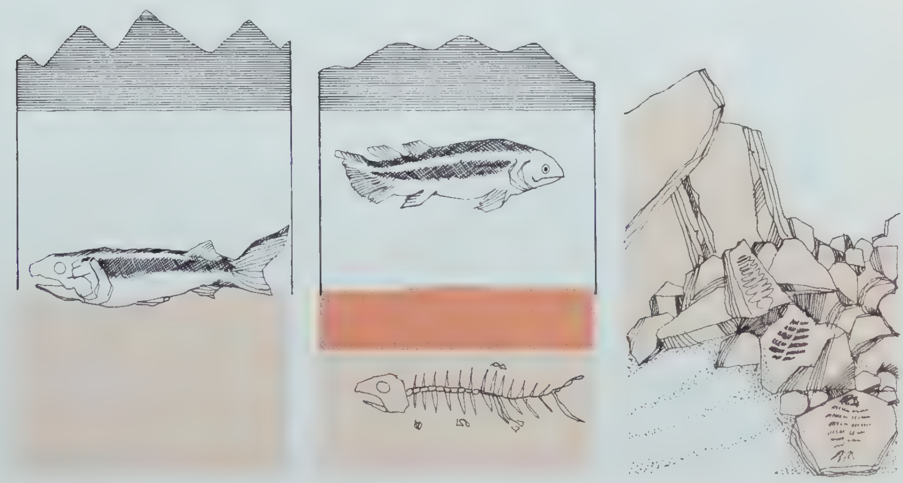
A number of factors affect fossilization, but there are two factors that are most important. First, if the organism has hard body parts, the chances of fossilization are greatly increased. Second, the plant or animal remains must be covered by some sort of protective material shortly after death. The environment of the organism normally determines the kind of covering material and the type of fossilization. For example, the remains of marine animals are commonly preserved because they fall to the ocean floor shortly after death and are buried by soft mud and sands (Figure 17–11). In general, the finer the sediment covering the organisms, the more likely that the remains will be preserved as fossils.

Although fossils are not usually found in igneous rocks, wind-blown volcanic ash and dust are sometimes suitable covering materials in which fossils are formed and preserved. In Yellowstone National Park, Wyoming, hundreds of trees were covered by volcanic ash and dust from eruptions during Early Tertiary time. At one place in the park as many as 27 fossil forests are found, one on top of the other.

The Yellowstone fossil forests are unique because many of the well-preserved trees are still upright, standing where they grew millions of years ago. The Early Tertiary forests of Wyoming must have been the home of many different animals, but no animal fossils have yet been found there. Can you suggest some reasons for the absence of fossilized animals?

Although most organisms change during fossilization, original remains are sometimes preserved intact. The soft parts of some animals, such as the Berezovka mammoth, have been preserved by freezing. Soft parts have also been fossilized by drying, a process that may produce

FIGURE 17–11
Describe the stages in the fossilization of a fish.



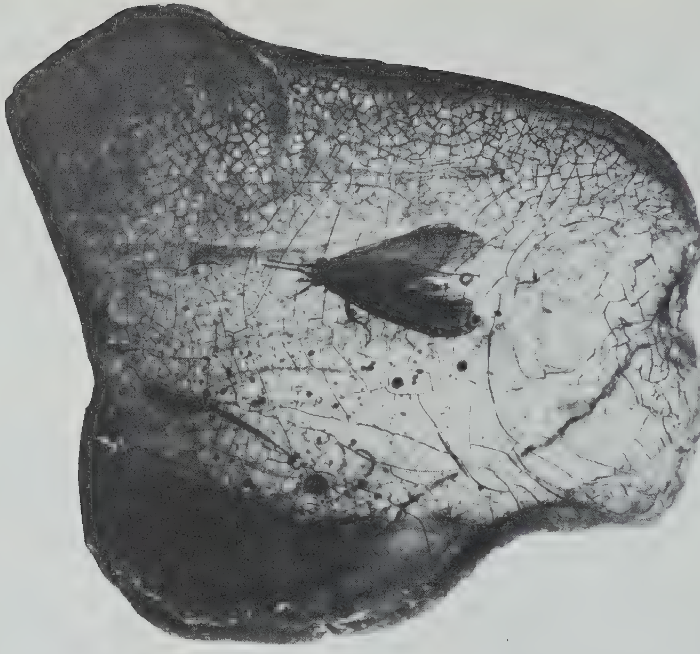


FIGURE 17–12
An insect preserved in amber.

FIGURE 17–13
These men carefully remove fossils from the La Brea tar pits.

a natural mummy. Insects and spiders have been preserved in **amber,** a fossil resin that flowed from certain cone-bearing trees (Figure 17–12).

Hundreds of thousands of practically unchanged bones have been removed from the La Brea tar pits at Los Angeles, California. (See Figure 17–13.) These tar pools, which formed on the earth's surface many thousands of years ago, are famous for their well-preserved fossils. Why do you think that so many animals might have lost their lives at this particular place?

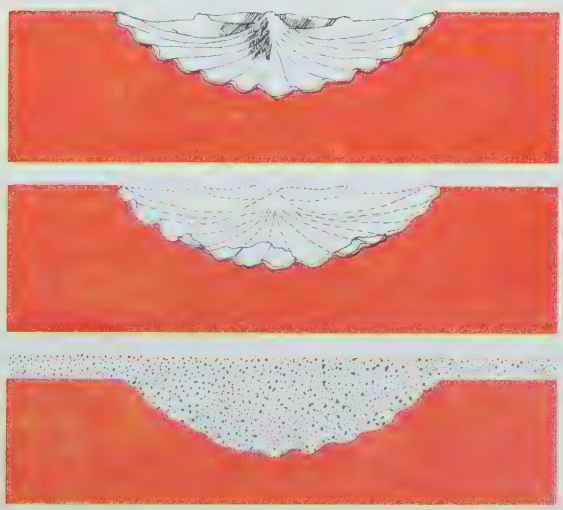
Organic hard parts normally change after they are covered by sediment. Mineral-bearing water seeping through the sediment may gradually dissolve calcium carbonate from a shell. The calcium carbonate could be replaced by silica or some other mineral in the water. Under other conditions the replacing solution may be rich in compounds of iron, magnesium, or calcium. In fossils that have been formed by replacement, microscopic details of the original hard parts may be beautifully preserved.

Many fossils have been formed through the gradual decay of organic material after burial. While slowly decomposing, the organic material leaves behind a thin film of carbon that shows a detailed outline of the original organism. (See Figure 17–14.) Such fossils are formed by **carbonization.**

Large numbers of fossils are found in the form of **molds** and **casts.** To see how these are formed, consider a seashell buried in ocean sediments. After the sediments have hardened under pressure, ground water may slowly dissolve the shell, leaving a cavity in its place. This cavity becomes a mold that preserves the markings of the shell. How would a ridge on a shell appear on this mold? As time passes the mold may be filled by mineral matter deposited by ground water. By this process, casts of the original shells are created. (See Figure 17–15.)

FIGURE 17–14
This fern leaf has been preserved as a thin film of carbon.

FIGURE 17–15
A shell buried in sediment. Remove or dissolve it and a mold is left (center). If the mold is filled in, a cast forms (bottom).



17–7
Investigating casts and molds

In this investigation you will make models of fossils and try to interpret evidence that gives you clues about the "organisms" you have preserved.

Procedure

Prepare both plaster molds and casts of various objects. Then exchange the plaster blocks containing your "fossils" with other members of the class. The following procedures should be used when making the plaster molds and casts.

making a mold

1. *Cover the various objects with a thin film of liquid soap or grease.*
2. *Place a small amount (about one-third cup) of water in the mixing container.*
3. *Slowly sift plaster through your fingers into the water, mixing the plaster and water as you sift. Add plaster until the mixture has the consistency of thick cream. If the mixture is too thick, add a small amount of water. If it is too thin, add more plaster.*
4. *Pour this mixture into another container. Tap the container to eliminate air bubbles. What will happen if there are too many?*
5. *Press the lightly coated object* ***gently*** *into the plaster.* ***Do not submerge it.***
6. *Allow the plaster to harden completely.*
7. *To expose the molds, remove the objects from the plaster.*

making a cast

1. *Lightly coat the surface of the block containing the molds with grease or liquid soap.*
2. *Mix another batch of plaster. Add a little food coloring to the water, if you wish. Cover the original plaster mold block completely with fresh plaster.*
3. *After the fresh plaster has set, separate the two blocks. The raised areas on the new block are the cast of the objects from which the mold was made. If it is difficult to separate the two blocks, use a screwdriver or chisel to pry them apart. If the blocks break, use them anyway. Many broken fossils are found, and the geologist still has the problem of interpreting them.*

Exchange your plaster casts and molds with someone else. Try to identify the objects that were used to make the molds or casts. What does the evidence tell you about the "organism"?

17–8
Fossils are clues to earth history.

One of the most important uses of fossils is in rock correlation. Some fossils represent plants and animals that only lived a short time in geologic history. While they were living, they may have been widely distributed. Some fossils are so characteristic of certain parts of geologic time that they have been called **guide** or **index** fossils. Guide fossils are especially useful in identifying the rock layers that contain them. It is known, for example, that dinosaurs lived only during the Mesozoic Era. Thus, when dinosaur remains are found, it is usually safe to assume that the rocks containing them are Mesozoic in age. However, paleontologists usually prefer to correlate rocks by means of groups of

fossils rather than correlate by means of a single fossil species. Why would this procedure be more reliable?

Ancient climates can also be inferred from fossils. Fossil reindeer have been found in Arkansas. Modern reindeer live in cold climates. This suggests that Arkansas in the geologic past had a climate different from what it is now. (Or did reindeer once live in a different climate?) The distribution of marine and land fossils have helped locate ancient lands and seas. This information is used to draw maps showing the margins of continents and oceans at various times during geologic history.

Fossils also serve as clues to lead geologists to rock formations that may contain valuable deposits of ore, coal, or petroleum. Certain kinds of microfossils are especially useful to the oil geologist. These fossils are so small that many of them are not broken by the bits used to drill oil wells. They can be brought to the surface almost undamaged and used as markers to guide the geologist.

The study of fossils has provided much support for the idea that living organisms have gradually changed and developed into their present forms. Fossils can be used to trace the development of plants and animals from the earliest known Precambrian forms to the more advanced species of today.

Thought and Discussion

1. Why are soft-bodied animals such as jellyfish seldom fossilized?
2. Name some materials that have been known to replace organic matter.
3. How are fossils useful to man?

Changing Patterns of Life

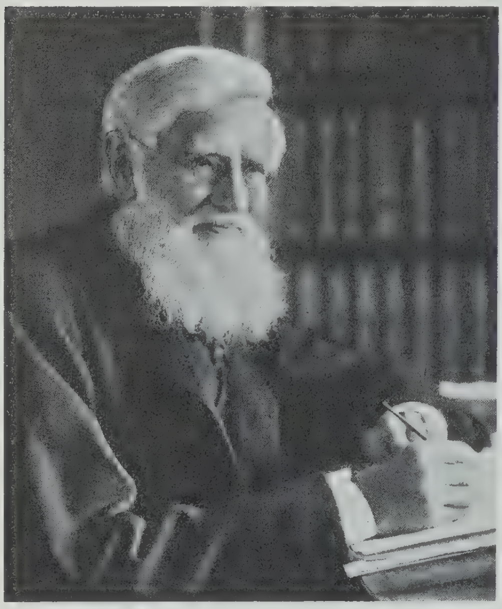
17–9
Plants and animals change through time.

The rock record is generally taken as evidence that living things may gradually change over long periods of time. The concept of gradual change provided the basis for theories of **organic evolution.**

In 1859, Charles Darwin, an English naturalist, published a book entitled *On the Origin of Species by Means of Natural Selection.* It contained a new theory about the evolution of plants and animals. Darwin's work was based on many years of extensive study of both living and fossil organisms. It started a controversy that has not yet ended. Some object to Darwin's theory because it disagrees with biblical writings. Most scientists feel that Darwin's theory has strong evidence to support it.

Darwin explained his theory of natural selection as follows:

1. There are variations or differences among the individuals in each species.
2. Some variations make an organism more likely to survive in his environment than others of his species. For example, creatures with greater speed than their fellows, or a tougher hide, or a color that blends in better with the surroundings have an advantage. You could say that the environment or nature "selects them" to survive.
3. These surviving organisms pass on their variations to their offspring.
4. As generations pass and favorable variations are continually selected, individuals become



Alfred Russel Wallace (1823–1913), a pioneer English zoologist, was a friend of Charles Darwin. Like Darwin, Wallace studied the distribution and nature of plants and animals all over the world. Wallace is best known, perhaps, for his studies of the geographic distribution of animals. He is less known for his contributions to the theory of evolution.

The history of science contains many instances where scientists have independently and simultaneously reached the same conclusions. Such was the case with the theory of natural selection. In 1858, a year before the *Origin of Species* was published, Darwin received a letter from Wallace who was working in the East Indies. Wallace enclosed an essay that he wanted Darwin to read. One can only imagine Darwin's surprise when he read this manuscript, for Wallace was proposing a theory of evolution almost identical to Darwin's. "I never saw a more striking coincidence," he wrote to Lyell, "if Wallace had my manuscript sketch written out in 1842, he could not have made a better short abstract!"

Wallace, like Darwin, had been struck by the marked differences between the plants and animals of the eastern and western islands of the East Indies. He had also read an essay by Thomas Malthus, an English clergyman. Malthus stated that population always increases faster than food supply. Wallace reasoned that a dwindling food supply would allow only the strongest species to survive, and in this way new species would eventually evolve.

This coincidence so amazed Darwin that he nearly yielded the honor of making the discovery to Wallace. Instead, both Darwin's and Wallace's essays were presented on July 1, 1858 at a joint meeting of the Linnaean Society in London. Thus, both men received credit for their work.

This coincidence prompted Darwin to complete the research that he had been doing for many years. His now classic book *The Origin of Species* was published in 1859.

Wallace, meanwhile, continued his study of evolution and animal distribution. He applied the theory of evolution to a world classification of animal species. These studies provided additional evidence that the continents were connected during earlier geologic time.

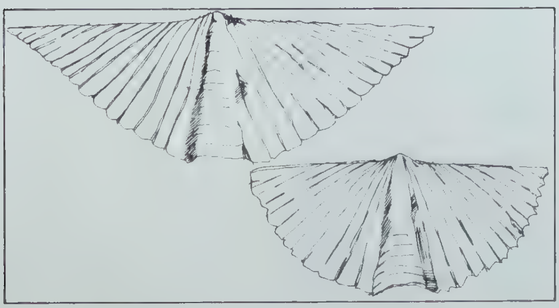
more and more unlike their early ancestors. In time, a new species may evolve from the old one. These new organisms are better adapted to survive in their environment.

Darwin saw many examples of plants and animals that seemed to support his theory of adaptation through natural selection. Most of his earlier observations were made in the Galápagos Islands. Located about 960 kilometers off the west coast of South America, these barren volcanic islands were an ideal outdoor laboratory. The islands contained a great variety of unusual plants and animals, but Darwin was especially interested in the birds. There were fewer species of birds than on the mainland. However, he found an unusually large number of finches. These finches were remarkably different in the shapes and sizes of their beaks. Darwin noted that the birds had beaks especially adapted for the type of food they ate. Some of the different beaks of the Galápagos finches are shown in Figure 17–16. Which birds had a beak well suited for picking up small insects? Which bird could extract insects from deep, narrow openings in the bark of trees?

When Darwin had completed his study of finches, he was convinced that the various beak types were the result of adaptation. Each kind of beak had slowly evolved and became specialized to peck, or bite, or dig up a different kind of food. The beaks were developed through natural selection over a period of about a million years.

FIGURE 17–16
Darwin's finches. What kinds of food might each of these birds eat?

FIGURE 17–17



17–10
Investigating variation and evolution

Do the two fossils in Figure 17–17 show an evolutionary trend? How could you find out? These same questions concerned paleontologists a century ago. The studies and interpretations of Charles Darwin helped provide the answers. In this investigation you have reproductions of two slabs of rock containing fossils.

You will try to determine for yourself what evolutionary trends might have occurred.

PROCEDURE

Examine the slabs of rock. How could you describe the differences and similarities of the fossils? Discuss with the class the characteristics that can be used.

Measure the length and width of each member of the population preserved on the slabs. For each slab graph these lengths and widths.

1. How do the fossils on each slab vary?
2. What similarities are apparent in each population? What differences exist?
3. What evolutionary trends might be exhibited?

FIGURE 17–18
Stages in the evolution of the horse. The bones and teeth (shown below) are preserved more often than other parts of the body.

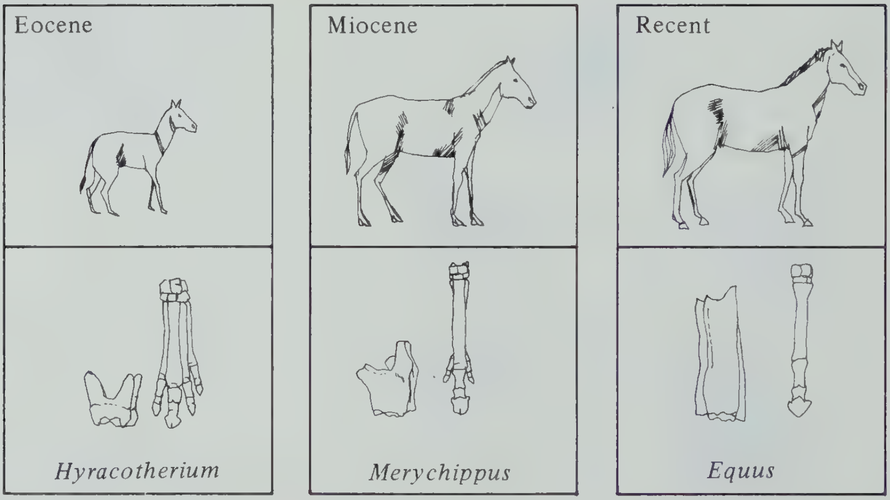
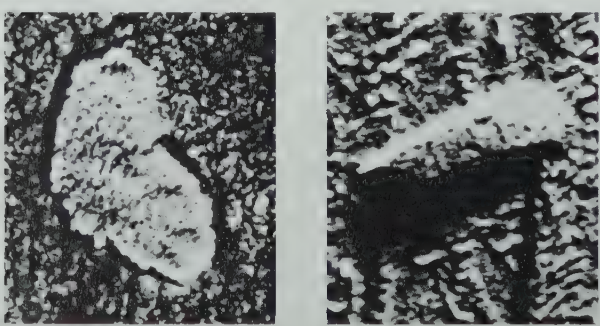


FIGURE 17–19
These bacteria-like fossils are less than one ten-thousandth of a centimeter in diameter.



17–11
The evolution of the horse

In looking for evidence to support his theory of evolution, Darwin studied many fossils. He noticed that fossils collected from older to younger rocks showed gradual changes. Paleontologists study fossils in much the same way today. By examining fossils from an undisturbed sequence of layered rocks, they can study many generations. This often makes it possible to speculate on how a species developed.

An evolutionary series has been proposed for the horse (Figure 17–18). According to the theory, the horse's development began in Paleocene time about 70 million years ago. These horses were leaf-eating forest dwellers about the size of a fox. Evidence shows that they lived in North America. The ancestral horse had four toes on each front foot and three toes on each hind foot. Each toe had a small hoof on the end. This construction was well suited for traveling on the soft, spongy forest floor. The horse had short teeth with small irregularities on the grinding surface. These molar-like teeth were adapted for crushing soft foods like leaves.

During most of the Tertiary Period the climate of North America grew cooler. Forests gradually became open, grass-covered plains. As the environment changed, these small horses adapted to it. Through a series of gradual changes over almost 70 million years and 10 million generations, the horse developed single toes with hard hooves for running over the harder surface of the plains. This change was accompanied by the development of longer biting and chewing teeth, a suitable adaptation for feeding on the coarse, dry grasses of the prairie. Each change was very slight and resulted from natural selection. Yet the accumulation of these small changes apparently produced the series of fossil horses.

The series of fossil horses is evidence that appears to support Darwin's theory of natural selection. The evolutionary sequence of the horse is not unique in geologic history. Similar lines have been established for elephants, camels, and many invertebrate animals.

Thought and Discussion

1. How does the theory of evolution relate to paleontology?
2. How did Darwin explain the process of natural selection?
3. How did the finches of Galápagos Islands adapt to their environment?

The Parade of Life

17–12
Paleozoic time: the age of invertebrates

No one knows when or where life first appeared on earth. However, fossils of simple life forms have been found in Precambrian rocks over three billion years old. (See Figure 17–19.)

More complex Cambrian fossils provide additional evidence that life was probably developing during Precambrian time. Not much is

Figure 17–20
The evolutionary tree of life.

known about these early forms because Precambrian organisms left very little evidence of their presence. However, evidence of life is abundant from the beginning of the Cambrian Period to the present. This clearly defined record stretches 600 million years back into time. (See Figure 17–20.)

To see how fossils are used to reconstruct the parade of life on earth, we can begin with the outline of an animal unlike any living organism. The **trilobite** is an extinct distant relative of the horseshoe crab, shrimp, and lobster (Figure 17–21). Scientists have studied thousands of trilobite fossils collected from marine sedimentary rocks. Features of trilobite shells suggest that the animals spent most of their time crawling through the mud on the ocean floor.

The fossil record of Paleozoic time shows the successive development of many new forms of invertebrates besides trilobites. **Invertebrates** are animals without backbones. During the Ordovician Period the first **vertebrates** (animals with backbones) also appeared. They were probably primitive, fishlike creatures that originated about 500 million years ago.

During Cambrian and Ordovician time life apparently was confined to the sea. Evidence in the rock record shows that during the Silurian Period both plants and animals colonized the land. The earliest land plants were probably simple and rootless. Fossils show that the first land animals resembled scorpions.

Near the middle of the Devonian Period about 375 million years ago, a specialized group of fish appeared called the "lobe-fins." These fish eventually gave rise to the amphibians. The earliest amphibians must have looked and behaved much like fish. However, the lobe-shaped fins were used as flipperlike legs. Gills could no longer be used for respiration. Instead, the

FIGURE 17–21
Reconstruction of a Cambrian sea floor showing trilobites, jellyfish, primitive sponges, and worms.

primitive lung of the lobe-finned fish could transfer oxygen from the atmosphere into the blood.

These amphibians were restricted to areas near water. They were the dominant land animals until the Pennsylvanian Period, when the first reptiles appeared. Reptiles do not need to live near the water. Their outer skin allows them to live in very dry places. Reptiles also have the ability to lay eggs out of water.

Fish, amphibians, and reptiles became common in Paleozoic time, but this era was really most favorable for marine invertebrates. Trilobites were numerous, especially on the bottoms of Early Paleozoic seas, but near the end of Paleozoic time their numbers began to decline. Finally, at the close of the Permian Period about 230 million years ago, the trilobites became extinct. What might be some reasons for the extinction of this once abundant and successful group of animals?

Brachiopods were animals with shells somewhat like clam shells (Figure 17–9). They were among the most abundant creatures on earth during Middle Paleozoic time. Sedimentary rocks in which their fossils are found show that most of these animals lived in shallow sea water. Throughout the ages certain varieties of brachiopods seem to have been able to adapt to different kinds of marine environments. They lived on muddy and sandy bottoms, in shallow and deep water, and near coral reefs. Perhaps this adaptability is one reason why brachiopods are still found in shallow seas today, nearly 600 million years after the first brachiopod shells were buried and preserved in the mud of a Cambrian sea. (How much longer would man have to inhabit the earth to equal this record?)

During the last part of the Paleozoic Era, erosion lowered the level of great areas of the continents. Large swamps formed in some of these areas. The partly decayed swamp vegetation slowly accumulated on the swamp bottom and was changed into peat. Long after the peat was buried and compressed beneath layers of sediments, it slowly changed into coal. These thick deposits of Paleozoic coal make up one of the largest concentrations of carbon on earth. It is certainly one of the greatest sources of energy available today.

17–13
Reptiles rule the earth.

Fossil-bearing Mesozoic rocks found at many places on the earth provide a fairly detailed picture of life during that era. Climate favored the development of reptiles, for it was much warmer during Mesozoic time than it is today. Beginning with the Triassic Period, reptiles had undisputed rule of the land. They ranged from less than a meter long to over 30. There were flying as well as sea and land forms of reptiles (Figure 17–22). Considering their numbers, it is not surprising that the Mesozoic Era is called the Age of Reptiles.

Among the many reptiles that evolved, the dinosaurs were particularly numerous and varied. Dinosaur National Monument in Utah is one of the best places in the world to see exposed parts of dinosaur skeletons. They are embedded in rock in the same position as when

the sediment covered them millions of years ago. (See page 321.)

The skeleton of the oldest known bird was found in southern Germany. It was embedded in limestone about 140 million years ago. This primitive bird could have been classified as a reptile. However, impressions in the rock showed that it was heavily covered with feathers (Figure 17–23). This was a most remarkable find. Not only is it the oldest known bird, but it also supports the theory that birds evolved from reptiles.

At the same time the vertebrates were advancing (during the Mesozoic Era), the land

Figure 17–22
Various Cretaceous dinosaurs: duckbilled (right), crested duckbills (left), "ostrich dinosaurs" (center background), and an armored dinosaur (center).

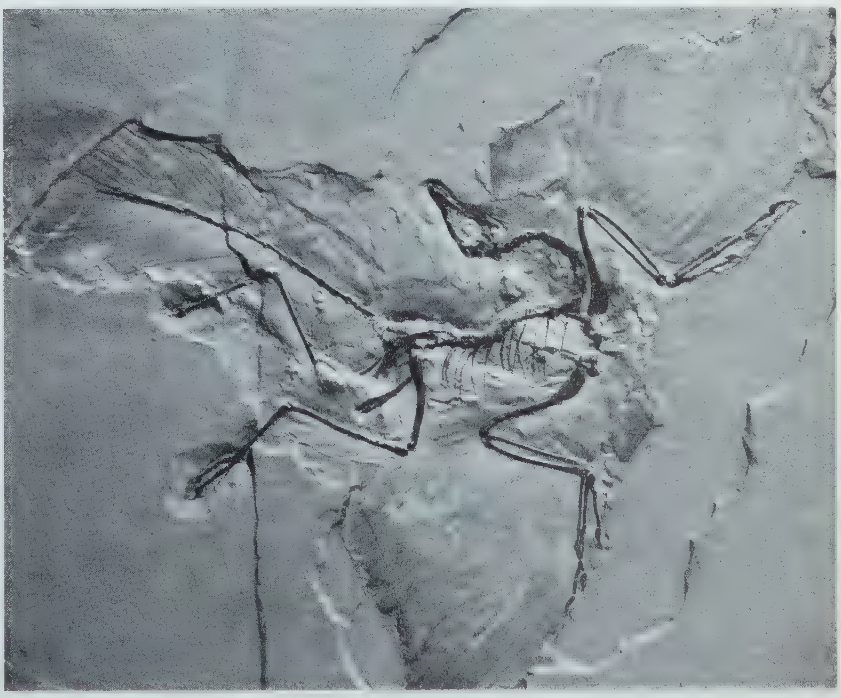


Figure 17–23
A well-preserved skeleton of Archaeopteryx, *the earliest known bird.*

plants increased in number and variety. During the Cretaceous Period grasses, fruit trees, and flowering plants appeared.

Toward the end of the Cretaceous Period the dinosaurs, flying reptiles, and most of the marine reptiles suddenly disappeared. After 140 million years the Age of Reptiles came to an end. Can you think of any reasons why these animals, which had so successfully adapted to such a wide variety of habitats, might have become extinct at the peak of their development?

17–14 The Cenozoic Era: golden age of mammals

Mammals began to appear during the Jurassic Period. The first mammals were primitive and

FIGURE 17–24 *A typical scene at the La Brea tar pits during the Pleistocene.*

FIGURE 17–25 *Neanderthal people. They probably lived at the entrance of caves, not deep within them.*

reptilelike, much like the early birds. The fossil remains of the first mammals are fragmentary. Evidence indicates that these creatures were about the size of a mouse. Although mammals did evolve rapidly during Jurassic and Cretaceous time, they were overshadowed by the reptiles. It was not until the Cenozoic Era that the mammals began to spread over the land and increase in numbers. They had developed into forms capable of adapting to a wide variety of environments. Might the extinction of the dinosaurs and other reptiles have anything to do with the rapid rise of the mammals?

Some mammals, like the giant ground sloths, woolly mammoths, and saber-toothed cats, flourished for several million years and then became extinct. (See Figure 17–24.) Others, like camels and horses, were the ancestors of modern forms.

As time passed in the Cenozoic Era, flowering plants and grasses increased. Many of today's trees such as the poplar, maple, elm, and oak began to spread rapidly over the land. Could these developments in the plant kingdom have played a part in the rapid rise of the mammals?

Late in the Cenozoic Era man appears to have developed from a group of manlike mammals. During Pleistocene time, man continued to develop into his present form. (See Figure 17–25.)

17–15
Investigating population growth

Man is now beginning to realize that he is facing an environmental crisis. Many of the hastily made and poorly planned changes that he has inflicted on his environment are now backfiring. He is paying both in financial terms and in more humanistic terms, such as mental and physical health.

Whenever environmental problems are investigated, it is usually found that the basic causes are the products of man himself, namely his advanced technology and his increasing population density.

In this investigation you are going to investigate the mathematical nature of man's population growth.

Procedure

Place a glass beaker on your desk with two objects in it. This will represent the earth which will hold only a finite population.

Place a number of paper cups in a row on your desk (10 should be enough). In the first cup, place two of the objects. In the second cup, place twice as many as in the first cup (4). Record on the outside of the cups the number of objects that have been placed in each cup.

In cups 3 through 10, double the number of objects that are in the previous cup (i.e., cup number 3 will contain 8, and cup number 4 will contain 16). Record the amount in each cup on the outside.

Take the beaker with the two objects in it and determine the beaker's height. What is the approximate volume in per cent that is **without** *objects? Record this on the table at 0 time.*

In 35 seconds, add the contents of cup 1 (i.e., 2 objects) to the beaker and record in the table the total population and the approximate per cent of the volume of the beaker that is

without objects. At 35-second intervals, add the contents of cups 2 through 10. Record your results.

Graph your results, total population versus time.

1. *Man's population on the earth is thought to have had a slow start with doubling periods as long as 1 million years. The present world population is thought to be doubling every 37 years. How would the mathematical nature of this growth rate compare to your investigation?*
2. *The present world population is about $4\frac{1}{2}$ billion people. The earth's radius is about 6,400 kilometers and about $\frac{7}{10}$ of its surface is covered with water. What is the present density of human population in terms of people per square kilometer? (Area of a sphere = $4\pi r^2$)*
3. *Assume a continuation of the present population growth rate. What will the density per square kilometer be 37 years from now? 111 years? 1,110 years?*
4. *Is space the only limiting factor in determining maximum human population? If not, describe others.*

17–16
What lies ahead?

Conditions on our planet have been suitable for the development of the human species. Earth has also provided us with the necessary raw materials and energy sources for the development of civilization. Modern technology has made our lives more pleasant. However, advances in technology are also responsible for many pollution problems.

Recent advances in medical science are prolonging our lives. But by living longer, man is adding to the problem of overpopulation. Man has successfully adapted to his environment so far. Can he continue to adjust to an ever-changing environment? Or will he—like the trilobites and dinosaurs—be recorded as just another extinction in the history of life?

As populations expand, we will need increasing amounts of limited resources such as fresh water, petroleum, and metal ores. This will place additional burdens on our already strained environment, and ecological problems will become even more critical. The earth is man's home and he should be more responsible for its care. How do you think man can help preserve and repair his natural environment?

Thought and Discussion

1. What can fossils tell us about ancient environmental conditions?
2. Which animal can adapt to the widest range of environments? Make a list of the evidence to support your answer.
3. Discuss some of the relationships between plant and animal development during the Cenozoic Era.

Unsolved Problems

Many fossils have been discovered, but some pieces in the puzzle of life history are still missing. For example when, where, and why did the

different animal groups develop hard parts such as shells? By the end of the Cambrian Period most of the major groups of invertebrates had developed hard parts. Yet in Precambrian time most organisms had poorly developed hard parts or lacked them entirely.

Did the vertebrates evolve from ancient relatives of the starfish or did they descend from the segmented worms? Scientists have suggested different answers to this question. Paleontologists are still searching for such missing bits of evidence in the fossil record.

At various times in geologic history, organisms such as the dinosaurs have become extinct. Although several explanations for this have been proposed, none of these theories can be proved. The world-wide extinction of a single group of animals cannot be explained from the available evidence. Mountain building, climatic changes, and migrations of predators cannot affect all the individuals in a group. What single or combined agents could have caused extinctions?

Scientists do not yet know exactly how plant and animal substances are changed into fossil fuels. If this problem could be solved, organic wastes might be used to manufacture fuels.

Chapter Review

Summary

Although life surrounds us, it is not always easy to distinguish living from non-living objects. In general, however, living objects are characterized by growth, response to outside stimulation, and the ability to reproduce. Living matter is composed of organic compounds. During the more than three billion years that life has been present on earth, it has spread to all parts of the earth.

Although the record of past life is incomplete, fossils have provided valuable clues to earth history. In studying fossils, the paleontologist uses many techniques of the biologist. He assumes that plants and animals of the past lived in much the same manner as their modern relatives.

The way an organism becomes fossilized depends somewhat on the original composition of its body and the physical and chemical conditions that surrounded the animal before and after burial. Most prehistoric organisms have not been preserved. Of those that have been fossilized, many have been destroyed through chemical and physical processes. Others will never be found by the paleontologist. In general, the older the rocks, the less evidence of life they are likely to contain.

Plants and animals have always been restricted in time, space, and environment. Thus, their fossil remains are valuable aids in interpreting earth history. Some of these fossils are used in the search for coal, petroleum, and mineral deposits.

Organisms vary in an orderly fashion. The consistent variation of horses is an example of the adaptation of organisms to a changing environment. This also appears to support Darwin's theory of organic evolution.

Rock records indicate that the first organisms to appear on earth were probably much less complex than those that developed during later geologic periods. The record of Precambrian life is scarce, but the fossil record is relatively clear from the beginning of the Cambrian Period. Although marine plants and animals were the dominant forms of Paleozoic life, vertebrate animals appeared early in the era and expanded rapidly. Fish, amphibians, and reptiles seem to have developed in the order listed. Following their first appearance in the Silurian Period, land plants evolved rapidly and soon covered much of the earth.

Reptiles reached the height of their development in the warm Mesozoic climates. The entire history of the dinosaurs is recorded in the rocks of that era. Mammals did not predominate until the Cenozoic. Then in a tremendous variety of forms they spread throughout the world. Modern types of trees, flowering plants, and grasses developed at the same time. The appearance of these new plants, the disappearance of the dinosaurs, and other changes apparently resulted in conditions ideal for the development of mammals. Man finally appeared late in the Cenozoic Era and has spread throughout the world. Despite his successful adaptation, problems of overpopulation and pollution threaten man and lead to speculation on his possible extinction.

Questions and Problems

A

1. What is meant by the term biosphere?
2. What are fossils?
3. Why are fossils not likely to be found in metamorphic rocks?
4. Why are microfossils especially useful to the paleontologist?
5. From what group of animals did birds and mammals probably develop?

B

1. A computer responds to outside stimulation. Is the computer alive?
2. Distinguish between organic and inorganic compounds.
3. Explain the role of decomposers in the calcium cycle.
4. How do fossils support the theory of organic evolution?
5. What features developed by the amphibians permitted them to live on land?

C

1. Discuss the various ways in which the biosphere, lithosphere, hydrosphere, and atmosphere may interact with one another. Describe the interfaces.
2. Outline the process of photosynthesis and explain why it is important to both plants and animals.
3. Show how the carbon, calcium, and water cycles are necessary for the support and continuation of life.
4. Explain how the differences of the Galápagos finches supported Darwin's theory of natural selection.
5. Describe the adaptations made by the amphibians as they evolved into reptiles.
6. What are some of the environmental problems faced by modern man? How might they be remedied?

Suggested Readings

Barnett, Lincoln and the editors of *Life*, *The World We Live In*. Golden Press, New York, 1956. (Paperback)

Beerbower, James R., *Field Guide to Fossils* (ESCP Pamphlet Series PS-4). Houghton Mifflin Company, Boston, 1971. (Paperback)

Fenton, Carroll L., and Fenton, Mildred A., *The Fossil Book*. Doubleday & Company, New York, 1959.

Hotton, Nicholas, III, *Dinosaurs*. Pyramid Publications, New York, 1963. (Paperback)

Matthews, William H., III, *Fossils: An Introduction to Prehistoric Life*. Barnes & Noble, Inc., New York, 1962. (Paperback)

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18. Development of a Continent

Paleontologists can sometimes discover directions of migrations by comparing the ages of certain fossils. For example, camels are now found in desert regions of Africa and Asia. But there is evidence that they originated in North America. The fossil camels in North America are found in older rocks than the rocks containing Asiatic fossils.

Horses also originated in North America. Some migrated to Eurasia, where they thrived and spread. But they died out in North America during the Pleistocene. Conquistadors reintroduced them to America in the 16th century.

We doubt that horses or camels could swim 85 kilometers across the Bering Strait. In the late Cenozoic a land bridge across the Bering Strait must have connected Asia and North America. A number of mammals, including man, migrated across this bridge. Those animals that could not survive the colder northern climate stayed on the continent where they originated.

You can see that the fossil evidence of migrations and evolution of plants and animals is also evidence for the changes and growth of continents. Life forms and the physical environment seem to have developed simultaneously.

The last chapter traced the development of life. This chapter is concerned with the growth and development of continents. There are important similarities and differences in the way the continents develop. All continents have mountains, plains, plateaus, and rivers. The arrangement and the ages of these features differ from continent to continent. For example, the Himalayas in Asia are younger than any major mountain range in North America. Since we are chiefly concerned with similarities here, North America can serve as a model.

Early History of North America

18–1
Investigating Precambrian Rocks

Figure 18–1 shows three cross sections of Precambrian rocks found on the north shore of Lake Huron in Ontario. Information was gathered from many outcrops and pieced together. Earth scientists think that these cross sections best represent the geology of this area.

Procedure

List the rocks shown in each of these cross sections in the order they were formed. If you are uncertain of the order, mark the rocks and explain why you cannot be sure.

Your teacher will then give you a list showing the ages of these rocks. The ages were determined by radioactive dating methods.

1. *Can you now put all the rock units in a relative time sequence?*
2. *Do the ages of these rocks agree with the order you worked out from the cross sections?*

This sequence of rocks in Ontario is typical of Precambrian rocks at many places in northeastern North America.

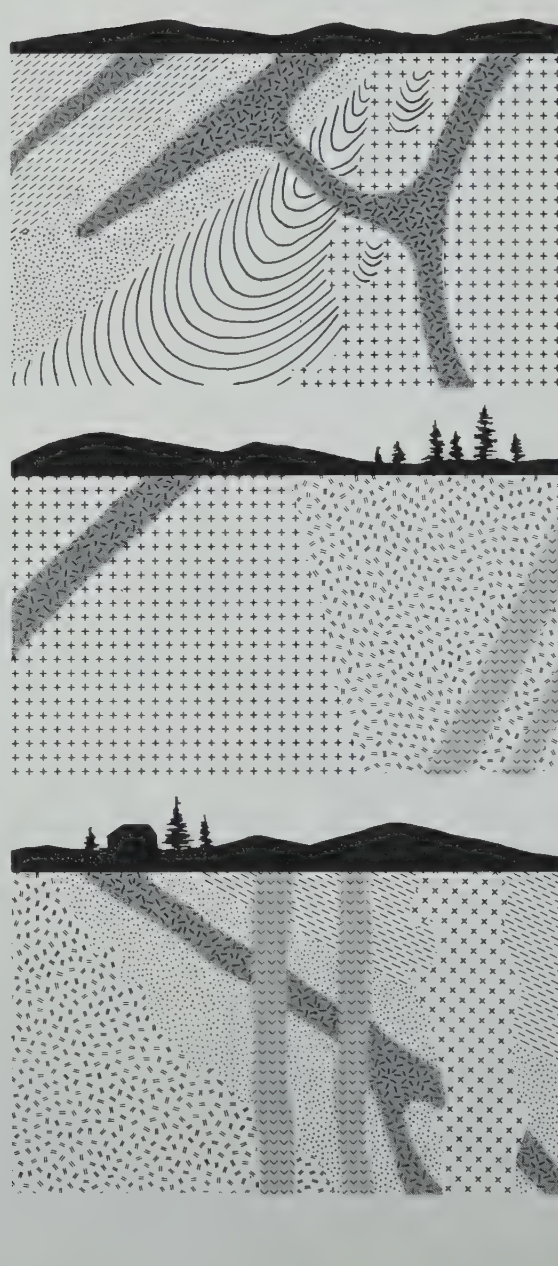


Figure 18–1
Cross sections of Precambrian rocks.

18–2
The Precambrian record

Large areas where Precambrian rocks are exposed are called **shields.** Each continent includes at least one shield, and some like Africa have more than one. Because the shield in

North America is found almost entirely within Canada, it is called the Canadian Shield.

Parts of the Canadian Shield contain alternating layers of lava flows and sedimentary rocks over 5,000 meters thick. Some of these deposits are exposed in low-lying areas (Figure 18–2). They appear to be roots of mountains formed so long ago that the highest parts have eroded away. The long, narrow belts where they are found are probably the sites of former geosynclines.

The Canadian Shield was an active area during Precambrian time. Mountain building occurred several times and in many places. The Precambrian record shows that erosion, sedimentation, volcanic activity, plutonic intrusion, and metamorphism were all involved in shaping the continent.

FIGURE 18–2
Folded and eroded Precambrian rocks in the Canadian Shield.

Figure 18–3 shows the areas in North America where Precambrian rocks are exposed. Some radioactive dates have been established for these rocks. The other dates shown in Figure 18–4 were obtained from samples taken from wells drilled down through younger strata to Precambrian rocks. Most of the dates come from igneous rocks intruded during mountain building. The dates show that all parts of North America did not develop at the same time.

Figure 18–5 shows this unconformity or gap in time between two rocks on the edge of the Canadian Shield. The overlying horizontal layers of rocks are Upper Cambrian, which makes them at least 50 million years younger than the underlying Precambrian rocks.

18–3
Four billion years of history

The record for the early history of the North American continent is not complete. Scientists think that the earth is at least 4.5 billion years old. However, rocks older than 3.3 billion years have not been found in North America.

Figure 18–6 shows the distribution of major rock types over the surface of North America. The oldest rocks known are metamorphosed sedimentary rocks. The source of the sediments that formed these rocks has not been located.

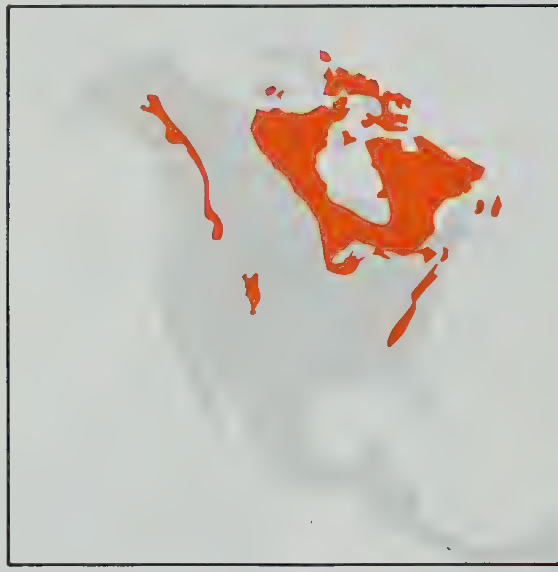
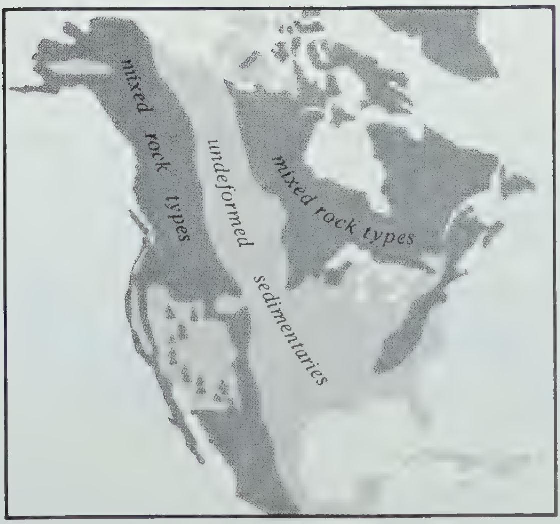


FIGURE 18–3
Precambrian rocks exposed at the surface in North America.

FIGURE 18–4
The distribution of radioactive dates from Precambrian rocks. The dates are in billions of years.

Figure 18–5
An unconformity between Precambrian and Cambrian rocks in Ontario.

Figure 18–6
The major rock types in North America. The mixed rock types include metamorphic and igneous rocks, as well as sedimentary rocks deformed during mountain building.



Possible stages of continental growth are outlined in Figure 18–7. These maps are based on the hypothesis that the continent developed from several smaller land areas. According to this hypothesis the first stage of development included rocks that are at least 2.3 billion years old. (Figure 18–7a).

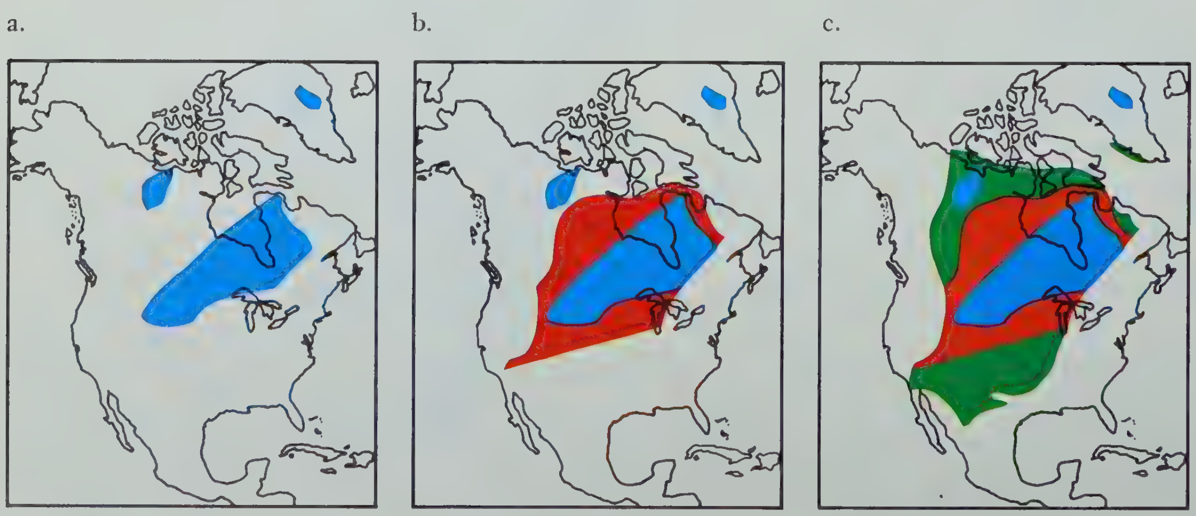
Rocks from geosynclines in the Shield are evidence that growth occurred at the edges of the continent. These geosynclines developed in areas receiving thick deposits of sediments. Later, the rocks formed in the geosynclines were lifted and folded to become part of the continent. Along the new edges, new geosynclines developed, and the mountain-building process was repeated (Figure 18–7b and c).

As continents grew, new environments became available for organisms. While adapting to these new environments, the organisms evolved more diverse forms. Thus, the increase in land area may have increased the rate of evolution of organisms.

The shapes of continents today, or at least large parts of them, are basically the result of this growth process. Continental drift implies that certain continental masses were torn apart or "welded" to other blocks. Such continents or parts of continents would be expected to have irregular edges. They would not have substantial accretion (slow growth) features. Thus, the separate processes of accretion and drift worked together to produce the present continental forms.

Some geologists think that portions of Newfoundland and Massachusetts consist of blocks that are more closely related to Europe than to the rest of the Appalachian Mountains. These geologists use continental drift to explain

FIGURE 18–7
Three stages in the growth of the North American continent:
a. *about 2.3 billion years ago*
b. *about 1.6 billion years ago*
c. *about 1.2 billion years ago*



their data. They theorize that these blocks remained behind when the present continents of Europe and Africa pulled away from the North American continent with which they had previously collided.

Thought and Discussion

1. What evidence is there that the Canadian Shield has been stable since the early Paleozoic?
2. What evidence is there that the Canadian Shield has not always been stable?
3. What evidence is there that North America developed from a smaller continent?

The Later History of North America

18–4
The Paleozoic record

During early Paleozoic time, the interior of the continent acted as a slowly and unevenly sinking platform. Shallow seas covered much of the platform, and thin layers of sediment were deposited. (See Figure 18–8.) Certain parts of the platform moved upward to form domes, and others moved downward, forming basins (Figure 18–9). The deposits of sediment that collected in the basins were thicker than on the domes.

Figure 18–9
Major structural features of the North American continent: 1) Michigan Basin, 2) Cincinnati Arch, 3) Illinois Basin, 4) Ozark Dome, 5) Llano uplift, 6) West Texas Basins, 7) Central Kansas uplift, 8) Williston Basin, 9) Colorado Plateau, 10) Columbia Plateau. The white bars show the locations of ancient and modern mountains.

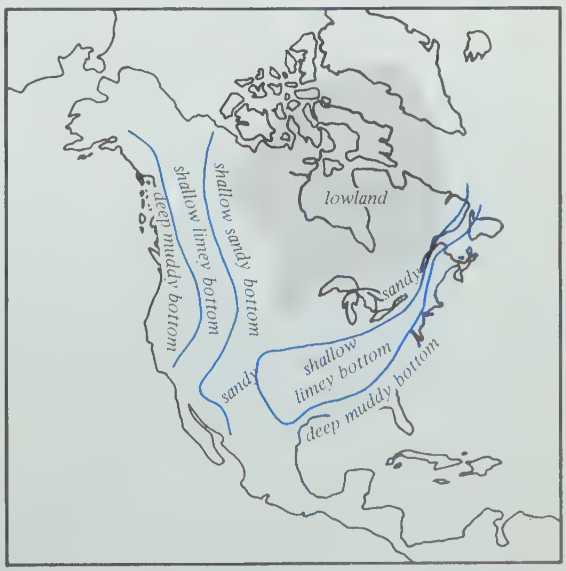


Figure 18–8
North America may have looked like this about 480 million years ago. This was a period of maximum coverage by sea.

Paleozoic rocks have obvious differences from Precambrian rocks. They often include extensive limestone, salt, and coal deposits. Paleozoic rocks also contain large, easily recognized fossils. For example, early sandstone and shales contain fossil trilobites and brachiopods. They were deposited on the bottom of the shallow Cambrian sea. (See Figures 17–9 and 17–21.) *Olenellus*, a trilobite, is found only in the oldest marine Cambrian rocks. When geologists find *Olenellus* in a rock, they assume that the rock is about 600 million years old.

The Paleozoic rocks deposited in geosynclines along the continental margins are much thicker than those in the interior. These geosynclines showed frequent volcanic activity and rapid sedimentation. In these zones folding and faulting of the rocks occurred. Vertical movements produced large islands marked by features such as domes.

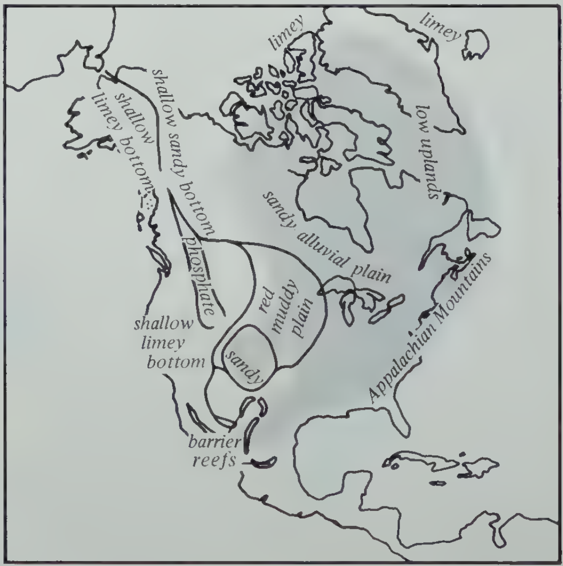
The rock sequences in the geosynclinal zones show the mountain-building history of the Paleozoic era. These zones mark a period of important continental growth that lasted 400 million years. By the end of that era the North American continent had grown outward from the older and smaller shield area. When mountain building stopped, the Appalachian mountain chain had become a new part of the continent. (See Figure 18–10.)

18–5 The Mesozoic-Cenozoic record

Late in the Mesozoic Era, the Rocky Mountains were pushed up from the sea. By early Cenozoic time 70 million years ago, they were higher than they are today. As they eroded, sediments were carried into basins between mountain ranges and eastward over the Great Plains. Some of these sediments were carried by rivers and streams into the Gulf of Mexico and the Arctic Ocean. By Mid-Cenozoic time, most of present North America was above sea level. Marine sediments were being deposited along the east coast and the Gulf coast. The Gulf of Mexico is a modern geosyncline.

The eastern part of North America had many volcanoes. We know this because igneous (especially basaltic) deposits are widespread. When those Mesozoic deposits were laid down, dinosaurs lived on the land.

Figure 18–10
North America may have looked like this 250 million years ago. After the uplifting of mountain ranges, the sea covered less of the land.



SIR CHARLES LYELL

While studying law at Oxford, Charles Lyell (1797–1875) became interested in geology. As a circuit lawyer, Lyell traveled through France and Italy. His observations of the landscape during these travels convinced him that Hutton's theories were correct.

Lyell believed the landscape had not been created by a series of catastrophes, as others thought, but rather by continuous earth processes that had been slowly going on since the beginning of geologic time. The same idea had been proposed more than a generation before by James Hutton. Lyell's data supported Hutton's theory. His three-volume book, *The Principles of Geology*, helped to bring this important idea to the attention of the world.

Through Lyell's careful work, the principle of "uniformity of process" became widely accepted. In 1838 he published the *Elements of Geology*, now regarded as a classical geological work.

Lyell later traveled to the United States and Canada in 1841 and wrote a number of papers about the geological features of North America.

ACTION *The locations of Precambrian, Paleozoic, Mesozoic, and Cenozoic rocks on the surface of North America are shown in Figure 18–11. Your teacher will give you some tracing paper. Place one sheet over Figure 18–11 and trace the boundary of North America and the boundaries of the Precambrian rocks shown on the map. Using separate pieces of tracing paper, repeat the process for the Paleozoic, Mesozoic, and Cenozoic rocks. Now compare the present surface distribution of rocks from these four eras.*

The Cenozoic rock record is more complete than any other era's. Some Cenozoic rocks are conglomerates, sandstones, and shales that were deposited by streams that flowed from uplifted mountain ranges. These rocks contain fossil horses, dogs, and ancestors of other familiar land animals and plants. The Cenozoic marine rocks are restricted almost entirely to the coastal plains region and some of the coastal ranges in California.

Fossil evidence shows that northern climates were once warmer. The region from Texas to North Carolina was tropical. Most of northern United States was subtropical, and Canada and

FIGURE 18–11

GEOLOGIC MAP OF NORTH AMERICA

FIGURE 18–12

NORTH AMERICA

WITH RELIEF IN OBLIQUE PERSPECTIVE

Alaska were in a temperate zone. About 15 million years ago the trend reversed. Climates grew cooler. The warmer belts were crowded near the equator, and all other regions became colder.

Thought and Discussion

1. How do geologists know that the early Cambrian seas were shallow?
2. In what era of geologic time are we now living?
3. What evidence shows that thicker rock layers in the geosynclines were formed during the same time interval as the thin layers found in the interior of the continent?
4. What destroyed the geosynclines that existed along the east and west coasts of North America during the Paleozoic and Mesozoic eras?
5. What might happen in the future to the Gulf coastal region where the present land surface is nearly flat, close to sea level, and underlain by great thicknesses of sedimentary rocks?
6. When did North America reach its present size and shape?

The Great Ice Age

18–6
Theory and evidence

In 1836 a young Swiss scientist, Louis Agassiz, began studying alpine glaciers. From his studies, he claimed that glaciers had once covered much of the Northern and Southern hemispheres. This theory had been discussed for many years, but had not been accepted.

Many of the boulders on the plains of northern Europe are composed of igneous and metamorphic rock. What is remarkable is that they are found hundreds of kilometers from the nearest outcrops of such rocks. Agassiz showed that these boulders could have originated *only* in Scandinavia. He proposed that the glaciers that once covered much of northern Europe had carried the rocks with them. He also suggested that alpine glaciers had been much larger about a million years ago. They were responsible for carving the sharp peaks and U-shaped valleys of the Alps.

Great sheets of ice also spread over more than half of North America at least four times. Grooves and scratches on the bedrock indicate

Figure 18–13
The maximum advance of the four great Pleistocene ice sheets over North America. The arrows show the direction of movement.

that the North American glaciers originated in Canada. The types of rock found, and the location of glacial deposits are further evidence for a Canadian origin. The glaciers flowed outward from centers near Hudson Bay and in the Canadian Rocky Mountains. (See Figure 18–13.)

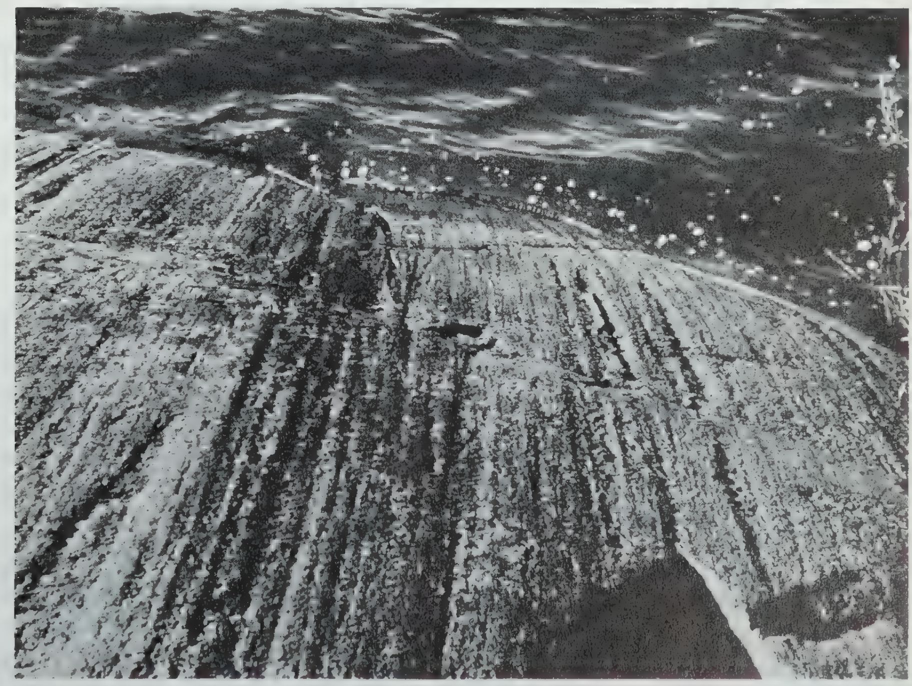
Between one and two million years ago, the glaciers expanded and melted at least four times. Each of these ice sheets covered the land for thousands of years. Between glacial advances, there were much longer periods when the land surface was free of ice. The climates were warmer than now. Radiocarbon dates of plant fossils found in glacial deposits show that the last ice sheet melted only about 10,000 years ago.

At times, over 25 per cent of the earth's land surface was covered by ice. Today, only about 10 per cent is ice-covered. Earth scientists debate whether we are currently living in an ice age. Until they learn more about the causes of glaciation, they cannot predict whether all glaciers will melt completely or begin to advance again.

18–7
Features left by glaciers

As ice sheets moved over the land, they picked up soil and weathered rocks. This rock debris polished, scratched, and grooved the bedrock the ice passed over (Figure 18–14). Glaciers scoured and deepened valleys and other low areas. Some areas were carved hundreds of meters deep. The Finger Lakes in New York and the Great Lakes were formed this way from

FIGURE 18–14
Glaciers grooved this plutonic rock on the shore of a lake in Sweden.



some shallow stream valleys. (See Figure 18–15.)

All the rock debris deposited by glaciers is called **drift.** People originally thought the loose material was deposited by melting icebergs drifting through water. As a result of Agassiz's work, drift was finally accepted as evidence of glaciation. Although its glacial origin is now known, the name drift is still used.

There are two main types of drift: **till** and **outwash.** Unsorted mixtures of clay, sand, and boulders are called till. (See Figure 18–16.) Many of the larger pieces have sharp angles, and their surfaces are covered with scratches and grooves. Around each basin of the Great Lakes, there are accumulations of till that mark the limits of a glacial advance.

Mixtures of clay, sand, and gravel that are sorted into layers are called outwash (Figure 18–17). When glaciers melt, the streams of meltwater pick up some of the rock debris. The largest material is deposited first. The finest material, such as clay, remains suspended in the water and can be carried away.

Because ice picks up more rock fragments from some places than from others, some parts of glaciers carry a larger load. As this material is deposited, it accumulates more in some places than in others. This is one reason that the surfaces of glacial deposits are so irregular and bumpy.

At times the ice over Hudson Bay was more than 3,300 meters thick. The weight of ice caused the earth's crust to sink. Where the ice was thickest, the surface was pushed down more than 500 meters. Hudson Bay is one of the depressions created by the ice.

When the ice melted and the load decreased, the surface began to rise to its original position. Some of the land surface still has not returned to its original level. The area near Niagara Falls is rising about 25 centimeters per century. At this rate, the movement will continue for a long time. What areas on other continents might have been depressed by ice sheets?

When the immense ice sheets accumulated on the continents, large amounts of water were temporarily stored as ice. Sea level was gradually lowered on at least four different occasions. Old beach deposits and wave-cut cliffs provide evidence for the change in sea level. (Why are some old beaches and other coastal features still above sea level?)

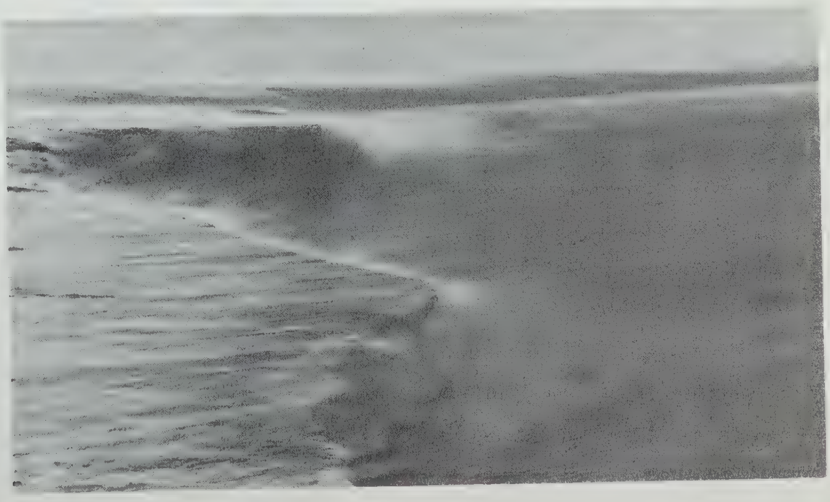
There are huge continental ice sheets that still cover Greenland and Antarctica (Figure 18–18). There are also many smaller ice caps, like the one on Iceland. And there are still

Figure 18–15
Lake Cayuga in New York was carved by glaciers.

Figure 18–16
Eroded glacial till left by the Casement Glacier near Glacier Bay in Alaska.

Figure 18–17
The outwash from this glacier in Alaska has formed a delta.

Figure 18–18
The Ross Ice Shelf, Antarctica. The cliffs tower up to 150 feet above the ocean.



thousands of valley glaciers on mountain slopes around the world. These valley glaciers are continually grinding away and reshaping valleys and mountain ranges into distinctive landforms. Over a million years ago when continental glaciers were widespread, valley glaciers were more numerous. The landforms that are created by valley glaciers can be seen in the Rocky Mountains and other high mountains on all continents.

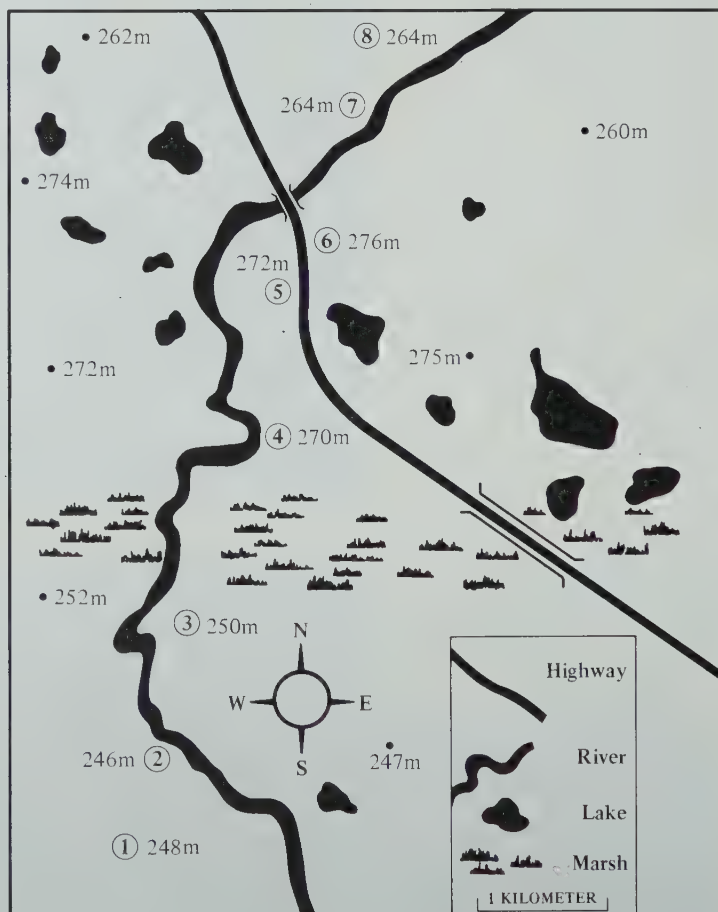
Troughs were cut by glaciers into some coastal mountain ranges. When sea level rose, some of these troughs became fiords.

18–8
Investigating an ice age puzzle

A glacier is a giant scraper several thousand feet thick, moving slowly over the land. Vast areas have been completely changed by the scouring and grinding of huge continental ice sheets and smaller valley glaciers. About a third of the world's landscapes exhibit features from the last glacial advance.

In this investigation you will examine an area that was once covered by an ice sheet.

Figure 18–19



Procedure

A map of a glaciated area appears in Figure 18–19. On the map are numbered stations. Geological data for each station is given in the table in Appendix E. The data was obtained from road cuts, stream banks, or drill holes made by geologists.

*Plot the elevation of each station on graph paper, using a scale of 1 centimeter = 10 meters. Connect the elevation points to show the shape of the land surface along a given line. This is called a **topographic profile.***

Plot the information from the data table for each station. Make a cross section by using either different colors or different geologic symbols for the rock and glacial deposits. Be sure to include a key to identify each color or symbol in your cross section.

Note that there are two kinds of glacial till that can be distinguished by their color.

1. *Which of the till layers is apparently the older one?*
2. *What evidence shows that a long time elapsed between deposition of the two layers?*
3. *What could cause this lapse of time between periods of deposition?*
4. *You will notice from the data that the bedrock has deep grooves at stations 5, 6, 7, and 8. Refer to your cross section. Which till are the south-trending grooves connected with?*
5. *Explain why there are no south-trending grooves at stations 7 and 8.*
6. *Describe the sequence of glacial activity in this area.*

Thought and Discussion

1. What evidence is there that the drift covering the northern United States and southern Canada was deposited by glaciers?
2. Why do scientists think that outwash is deposited by water rather than by ice?
3. What evidence indicates that there was more than one glacial advance during the Pleistocene Epoch?
4. How can earth scientists locate the centers from which the ice sheets advanced?
5. Are we living during an ice age, in a period between glacial advances, or at the end of an ice age? What is your evidence?

Unsolved Problems

Because fossils are rare in Precambrian rocks, it is hard to correlate such rocks from different parts of North America. Therefore, there is no detailed history of the Precambrian continent. Many problems relating to the continental origin and its early development remain unsolved.

Mountain building has occurred frequently during most of geologic time. However, there is a 500 million year gap between the last Precambrian mountain building and the first Paleozoic mountains in North America. This interval is almost equal to the combined length of the Paleozoic, Mesozoic, and Cenozoic eras. The lack of records of sedimentation, mountain building, or metamorphism for this period of time is puzzling.

Scientists are trying to discover what changes in climate cause continental glaciers to origi-

nate, develop, and expand over large areas. They also need to know what conditions cause glaciers to shrink and finally disappear. For glaciers to form, average annual temperature must be so low that more snow accumulates during winter than melts during summer. One current hypothesis suggests that glaciers in the Northern Hemisphere expand when the Arctic Ocean melts and retreat when the ocean surface is frozen.

Chapter Review

Summary

The North American continent has existed for more than three billion years. It is not known whether it was a feature of the earth's crust when the planet was forming. The ages of the igneous rocks from different parts of North America suggest that the continent grew in stages. New crustal material was added by mountain building at the margins of the continent. There is also evidence that North America broke away from a larger continent and drifted to its present position.

Perhaps during Precambrian time, and certainly later, seas alternately advanced and retreated over the interior of the continent. In these seas and on the adjoining land, animals and plants evolved, and sediments were deposited.

The geosynclines on the continental margins were mobile regions for long periods of time. The geosyncline in eastern North America was subjected to folding and intrusion by plutonic rocks. It was uplifted during the Paleozoic and early Mesozoic Eras. The geosyncline of western North America was uplifted during the Mesozoic and early Cenozoic Eras.

North America reached its present outlines late in the Cenozoic. Earthquakes, volcanic activity, and movement along active faults, especially along the Pacific Coast, show that it is still changing. Not enough is known about earth processes to precisely predict future developments.

The Pleistocene ice sheets were the most recent major events in the development of North America. The glacial advances affected both the development of man and the migration of humans across the earth. Most of North America is now free of ice. However, there are extensive continental ice sheets on Greenland and Antarctica. It is not known whether glaciers will advance again in the near geologic future. The ice may retreat and not return again until another great ice age.

Questions and Problems

A

1. What types of rocks are generally associated with plains and plateaus? with mountain ranges?
2. Why is the trilobite *Olenellus* useful for rock correlation?
3. What principles are used to arrange layers of rock in sequences?
4. In what ways do deposits of till and outwash differ?
5. What features of glaciation are used to indicate the direction in which the ice moved?
6. The Great Lakes and Hudson Bay occupy

large depressions. How were these depressions formed?

B

1. Describe the arrangement of mountains and lowlands in North America. Why are they arranged in this way?
2. Igneous and metamorphic rocks commonly are exposed in mountain ranges. How do you explain their presence at the surface of the Canadian Shield?
3. Why is the rock record of the geologic history of a continent less complete for earlier than for later eras?
4. What might the earliest living things have been like? Why have no fossil traces of them been found?
5. Why are some fossils useful for correlating sedimentary rocks but not for explaining the environments in which the rocks formed? Why are other kinds of fossils useful for explaining the environments in which rocks formed, but not for correlation?
6. There have been several explanations for the migration of animals and plants from continent to continent. List some of them and explain what kinds of evidence are needed to support each.
7. What evidence indicates the presence of extensive glaciation in the Northern Hemisphere during the Pleistocene Epoch.
8. Parts of North America are still reacting to the presence of the tremendous weight of Pleistocene ice. What are these reactions and where are they noticeable?

C

1. If the oldest known rocks are sedimentary, does this mean that the first rock-forming process that affected the earth was sedimentation?
2. What does the presence of fossil coral reefs in arctic regions probably indicate about the ancient climate of those regions? What other possible explanation could there be?
3. How will studies of the ocean floor help to explain the origin of continents?
4. There are indications that climates in the Northern Hemisphere are gradually becoming warmer. What effect could this have on the remaining glaciers and sea level? How might this be related to the Pleistocene ice age?

Suggested Readings

Books

Dott, R. H., Jr., and Batten, R. L., *Evolution of the Earth.* McGraw-Hill Book Co., New York, 1971.

Moore, R. and the editors of *Life, Evolution.* Time, Inc. (Life Nature Library), New York, 1962.

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Glaessner, M. F., "Precambrian Animals." *Scientific American,* March 1961. (Also Scientific American Offprint #837, W. H. Freeman & Co., Publishers, San Francisco.)

Harland, W. B., and Rudwick, M. J. S., "Great Infra-Cambrian Ice Age." *Scientific American,* August, 1964.


UNITED
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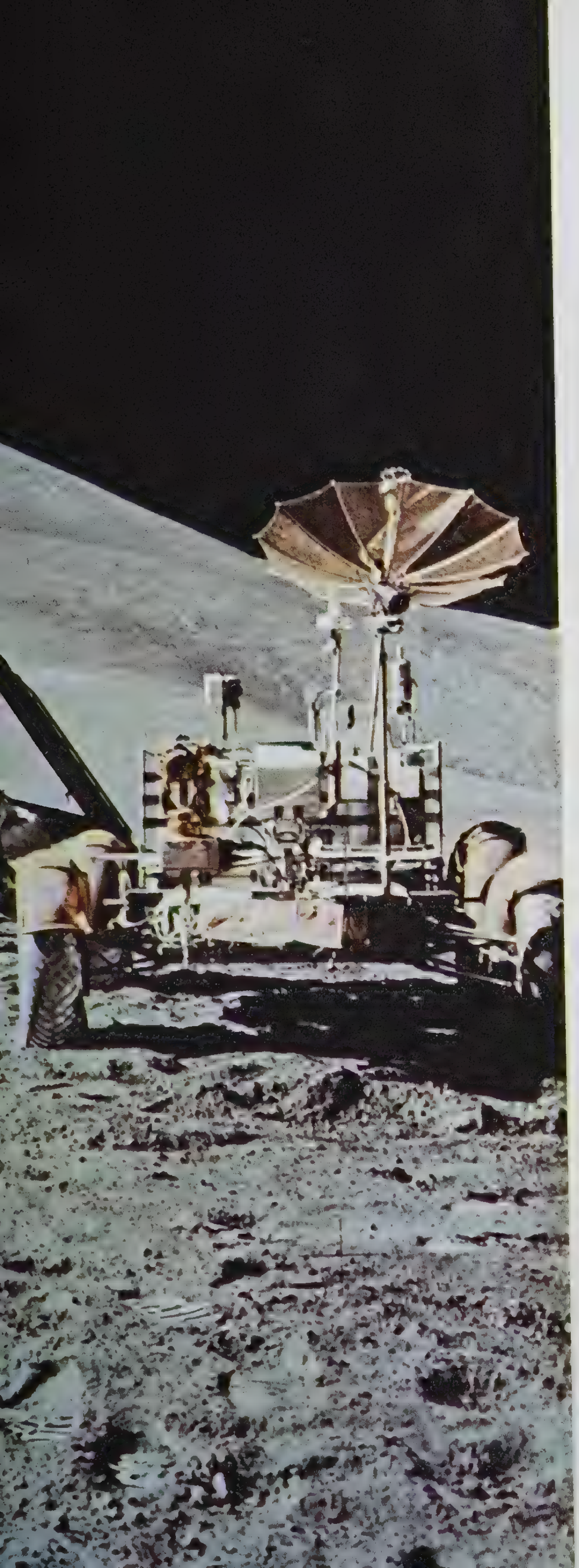
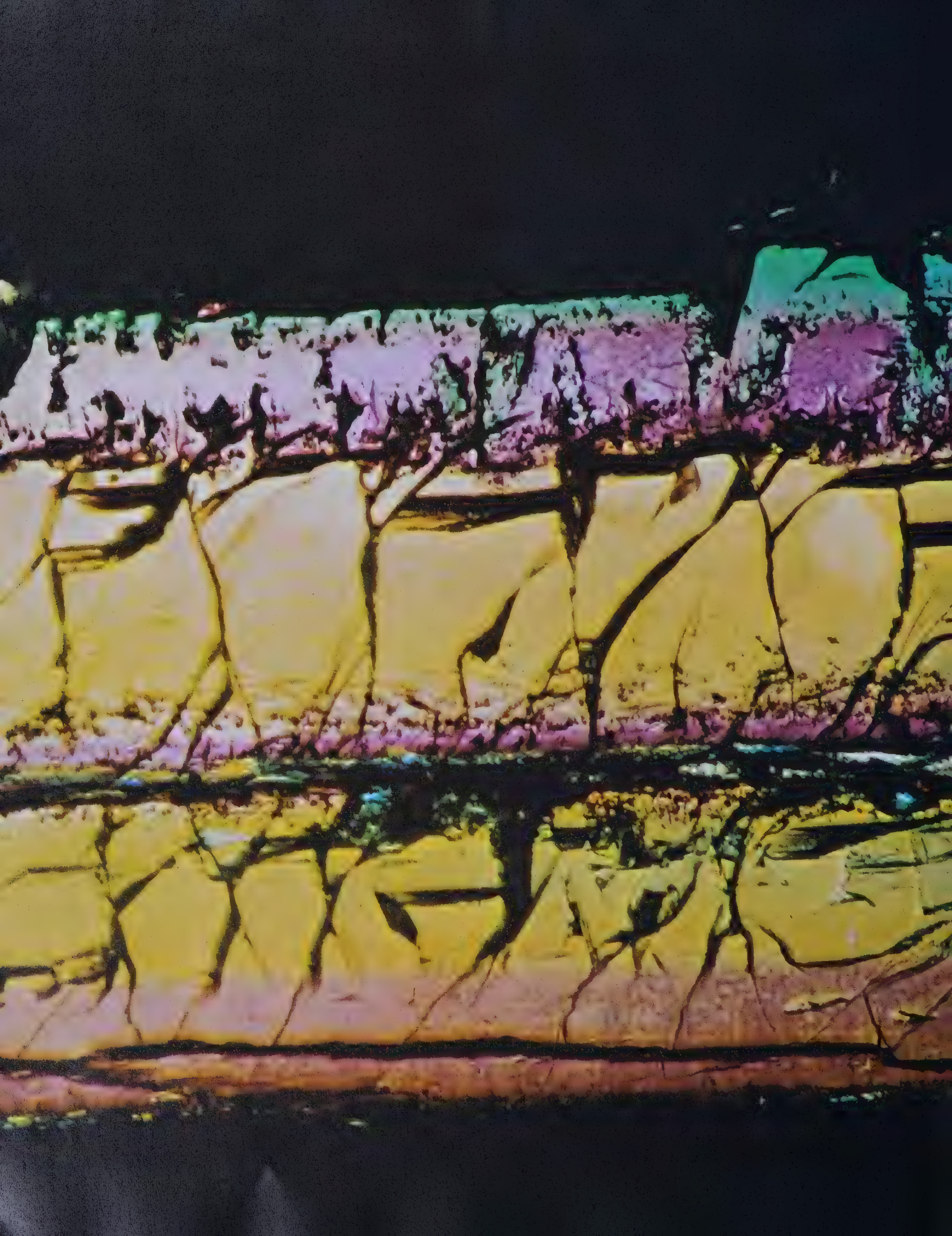


unit five

Exploring the Universe



19. Exploring the Moon

So far we have been chiefly concerned about the earth, its processes and history. But we cannot fully understand the earth until we also understand the moon. The passive and pockmarked face of the moon still records many of those earliest events of Precambrian history that were erased long ago from the face of the earth.

The oldest known rocks at the earth's surface are 3.5 billion years old, and these rocks are sparse. No record of the earth's first billion years of life has yet been recognized. We hope moon rocks will unfold for us a complete record of events that have taken place in this corner of the solar system since it formed at least 4.5 billion years ago.

Scientists have already learned many things from moon rocks. The pyroxene crystal on the opposite page was collected by the Apollo 12 astronauts. The photograph was made under a microscope with special light that produced the vivid colors. The yellow sections have little calcium, while the pink and purple areas are calcium-rich. The green areas contain more iron. These distinct zones indicate that the rock crystallized rapidly at the lunar surface, perhaps after a meteorite impact.

It was only in the 1960's and 70's that we gained massive amounts of information and great understanding of the moon and its history. What is particularly monumental about the "60's" is that the President of the United States set a national goal to land a man on the moon before the end of the decade. Scientists believed it was possible to land on the moon. But the undertaking was vast. It required the coordinated activities of hundreds of thousands

of people. There was always a serious question whether it could be done before the end of the 20th century. Although President Kennedy did not live to see it, the first man ever to set foot on our sister planet stepped out of the space capsule onto the surface of the moon on July 21, 1969.

Unlike the great discoveries of all previous ages, this one took place as millions of people watched on television. Never before in man's history had it been possible for more than a few people to witness major scientific or technological discoveries. Now, millions of people around the earth watch and hear the astronauts explore where no man nor any other form of life has ever been.

Lunar Landscapes

19–1
The view from earth

Let us now make an imaginary rocket trip to investigate the moon. On this expedition we will relive the experiences of scientists as they made their observations from earth and as they planned to actually visit and study the moon.

Before lift off, we must look at the face of the moon and see what we can learn from a distance. This exercise is of great importance in choosing landing sites. We must land our space vehicles in a safe, level place. We must also choose our landings near interesting sites that may tell us about the nature of the moon and its origin.

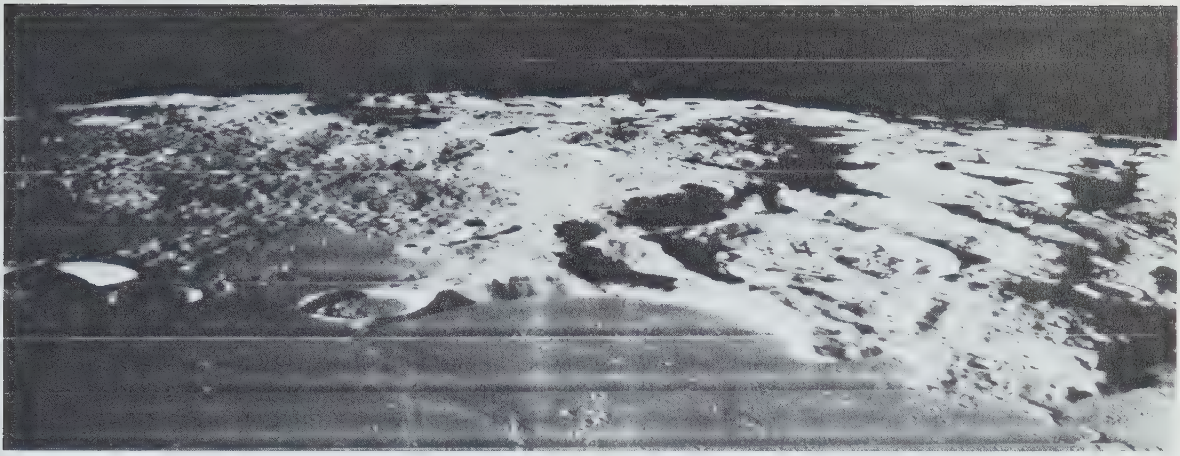
ACTION *Use the information you gain by studying the moon from a distance to select three suitable landing sites. Give the reasons for your choices.*

Look at the full moon with binoculars. You will see that the moon has two types of landscapes, one dark and the other much lighter. The light areas are usually called highlands or continents—to distinguish them from the lowlands or seas. Close examination of the highlands shows that the light areas are covered with **craters** of all sizes. (See Figure 19–1.) The word crater simply means a bowl-shaped depression.

The dark areas are much smoother and lower than the highlands. They also contain craters, but not as many large ones as the highlands. Early astronomers thought these dark areas were oceans and called them **maria** (MAH-ree-ah), the Latin word for seas. Although there are no oceans on the moon, the ancient name remains. In fact a new mare (MAH-ray, singular of maria) was named after being photographed by the Ranger 7 spacecraft. It is Mare Cognitum, the Known Sea. (See Figure 19–2.)

Maria sometimes have features called **mare ridges,** or **wrinkle ridges** (Figure 19–3). These ridges are hard to see unless the sun's rays slant across the moon at a low angle. They are several kilometers wide and sometimes hundreds of kilometers long, but only a few hundred meters high. (What features on earth do these remind you of?)

Except for the maria, the chief features on the moon are craters. The largest of these



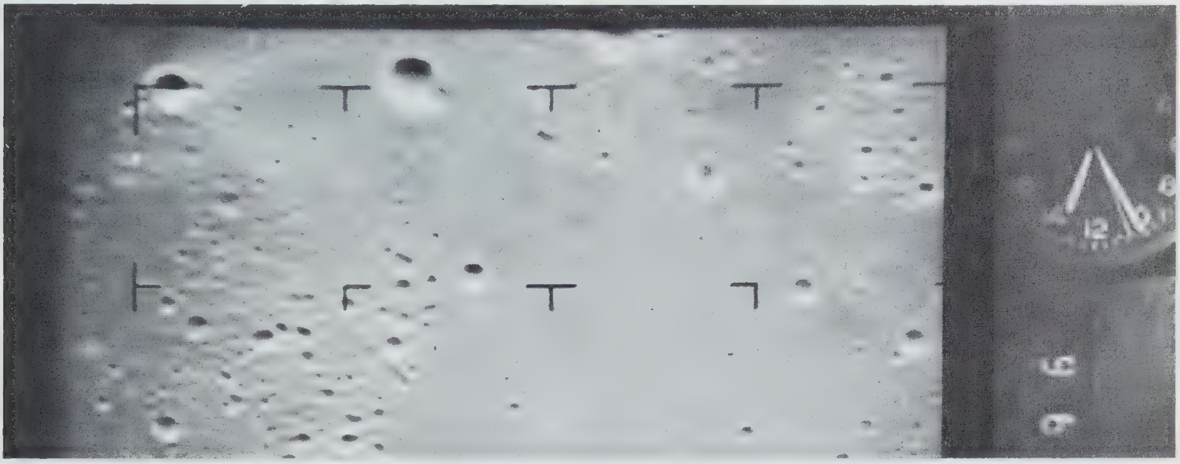
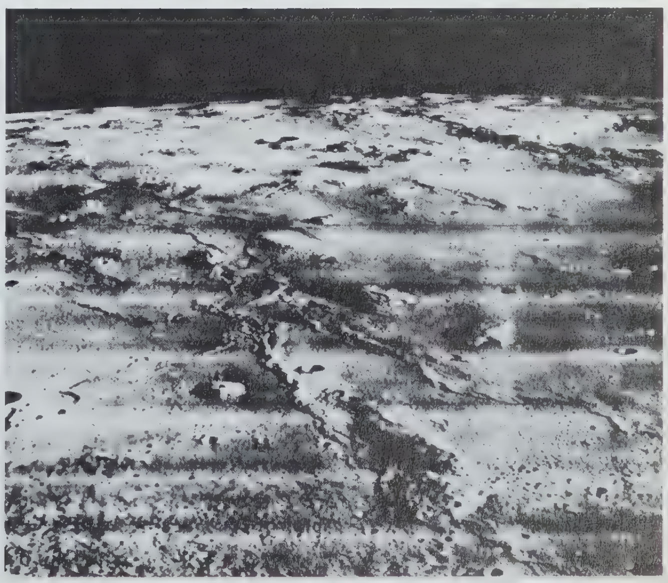
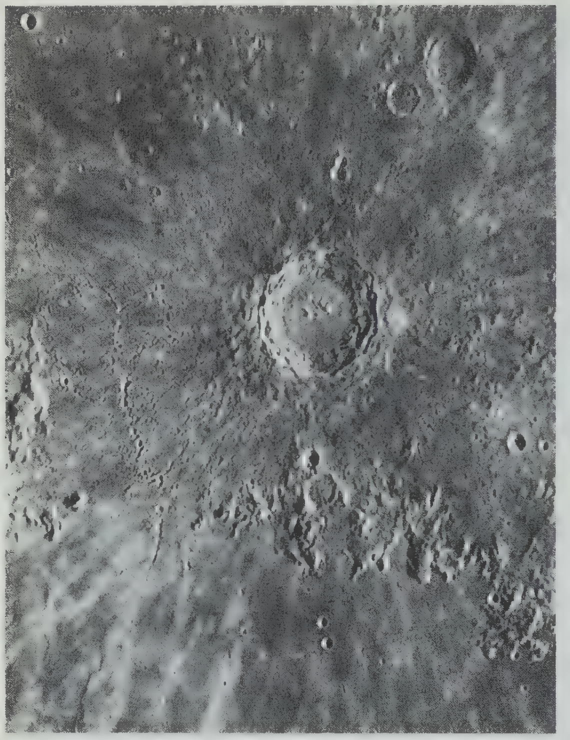


Figure 19–1
(top) What is the most noticeable feature of the lunar highlands?

Figure 19–2
Mare Cognitum. How does it compare to the lunar highlands?

Figure 19–3
(right) Wrinkle ridges and domes.





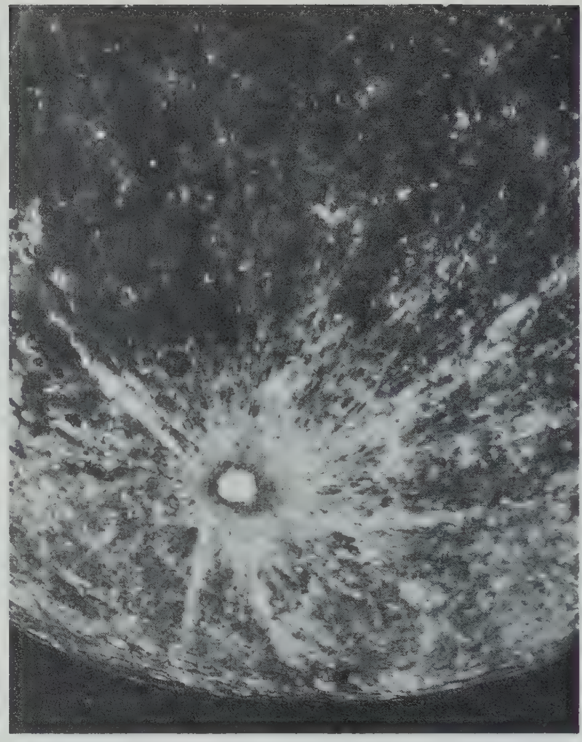
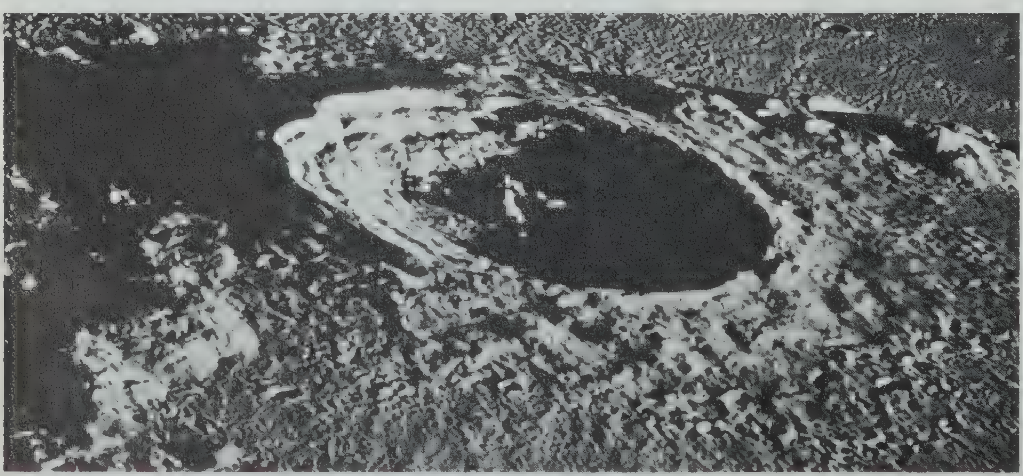


Figure 19–4
(top left) The crater Copernicus. Can you find the central peak and the rays?

Figure 19–5
(top right) Compare Tycho shown here with Copernicus.

Figure 19–6
How does Eratosthenes differ from Copernicus and Tycho?



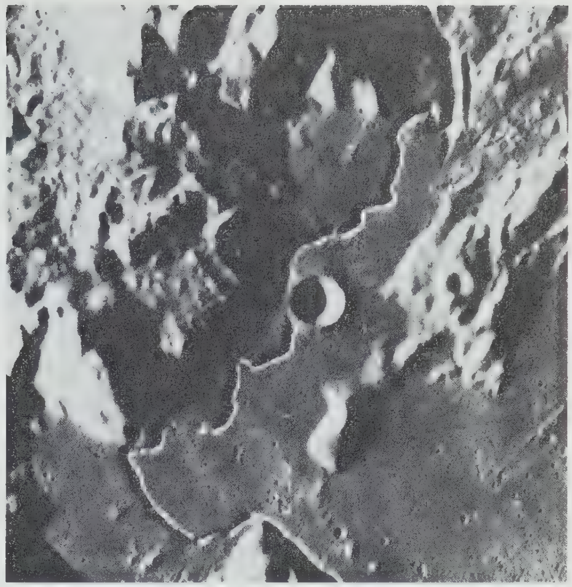
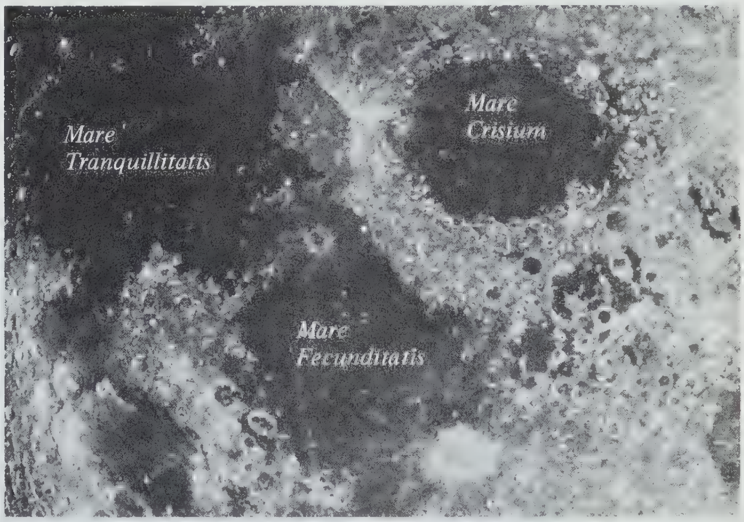


Figure 19–7
(top left) The crater Archimedes on the edge of the Mare Imbrium.

Figure 19–8
(top right) Hadley Rille snakes across the lunar landscape.

Figure 19–9
(center) Several lunar maria. What features do they have in common?

Figure 19–10
(bottom) A row of small chain craters.



craters (larger than any known on earth) have diameters of 300–400 kilometers. The crater Copernicus, named after the famous astronomer, is one of the boldest on the visible face of the moon. (See Figure 19–4.) It has a diameter of 92 kilometers and contains a central peak. The crater's inner wall is made up of terraces formed by slumped blocks of rock. The outside rim of Copernicus is a light-colored, rough blanket of rocky material believed to have been ejected, or thrown out, from the crater. This rock is called the **ejecta blanket.** Deposits of white material called **rays** radiate from some of the lunar craters. There is no distinct boundary between the ejecta blanket and the rays. How do you think the rays were formed?

Tycho is another crater like Copernicus. Because of its tremendous ray system, Tycho is easily visible with binoculars at or near full moon (Figure 19–5). Many craters have no visible rays, for example, the crater Eratosthenes. It is somewhat rounded, as if by erosion. (See Figure 19–6.) What does this suggest about the rays?

Look again at another crater, Archimedes in Figure 19–7. Archimedes does not look like the other craters. However, closer study reveals that it too has a rim, a series of terraces one within the other, and at least part of an ejecta blanket. It looks different because it has been filled and partly surrounded by dark mare material.

Mare Crisium (Sea of Crises) seems to be a larger version of Archimedes. Mare Fecunditatis (Sea of Fertility) and Mare Tranquilitatis (Sea of Tranquillity) seem to be larger versions of Mare Crisium. (See Figure 19–9.) These circular depressions ranging in size from Copernicus to Mare Tranquilitatis include almost all the major topographic features of the moon.

Chain craters are rows of small craters only a few kilometers in diameter. (See Figure 19–10.) They may occur almost anywhere—in the highlands, on the maria, or on the floor of large craters. Some chain craters are surrounded by deposits of dark material.

Another unusual feature of the lunar landscape are **rilles** or valleys on the moon's surface, like Hadley Rille investigated on Apollo 15 (Figure 19–8). In some places the rille is obscured by a chain of craters built up along its edge. (Could rilles and chain craters be related?) The rilles are generally thought to be faults formed by subsidence of the surface. Lunar Orbiter 2 has also revealed domes that seem related to eruptions of materials from within the moon. (See domes in Figure 19–3.)

19–2
Investigating landscapes on the moon

Few places on earth have features like the moon. Does this mean that the geological principles used to study earth history won't work on the moon? For example, does the principle of superposition hold true on the moon? In this investigation you will try to answer these questions. Use the transparent sheet and crayons to help work out the history of the lunar area in Figure 19–11.

Procedure

Examine the landscape shown in Figure 19–11 and in the geologic map of the area prepared

by the United States Department of the Interior.

1. What seems to be the last feature that formed on the surface? What seems to be the earliest feature?

Starting with the most recent event, try to list the sequence of events that took place to produce the landscape. Compare the history you have developed with the history indicated on the geologic map provided by your teacher.

2. In what ways did your interpretation differ from the map? In what ways was it similar?
3. If you were to land in this area, what five spots would you visit to learn the most about lunar landscape features?

FIGURE 19–11
A lunar landscape in the north central portion of the moon. The large crater is Archimedes.

19–3 The evolution of the lunar landscape

The lunar surface is a jumble of craters, rilles, and rays. The picture begins to make sense if you remember that the surface features may be divided into two major kinds: the maria and the highlands.

First, you must distinguish between the dark mare material and the circular depressions that it fills—the **mare basins.** Scientists once thought that the mare material was lava because it looked as though it had flowed over the moon's surface. However, evidence from radar reflections indicated that the moon was covered in places with deep dust rather than lava. In addition, the Ranger and Surveyor pictures showed few features typical of lava. But new information from lunar probes and Apollo missions shows that the mare material *is* ancient

lava. By studying the Apollo rocks, scientists have determined that lunar lavas are less viscous than earth lavas. Thus, lunar lavas flowed easily and quickly over the lunar surface. The lava has been struck repeatedly by meteorites over many millions of years. It has thus been reduced to rubble.

The origin of lunar craters is another major question. There are two possible explanations. One theory states that craters are large collapsed volcanoes, or calderas (call-DER-ahs). Earthly versions are the Darwin Caldera in the Galápagos Islands and Crater Lake in Oregon (Figures 19–12 and 19–13). The second theory states that large meteorites crashing into the moon like bombs blasted out the craters.

Scientists who study volcanoes on the earth noted that calderas resemble lunar craters. For example, Crater Lake has a central peak. This is actually a small cinder cone that developed

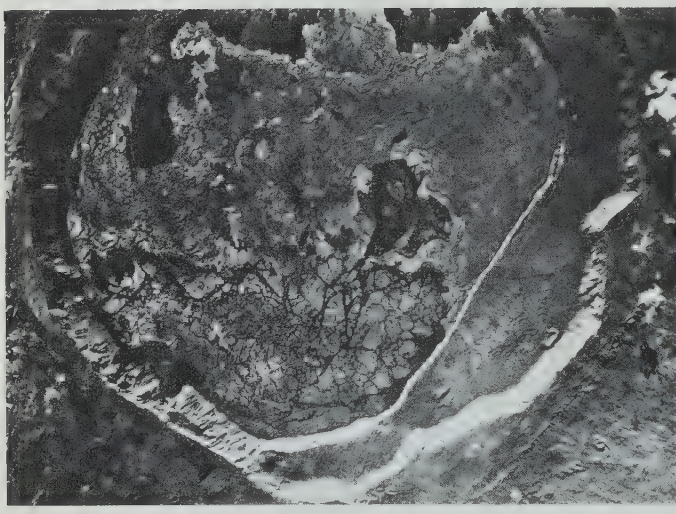


FIGURE 19–12
The Darwin Caldera in the Galápagos Islands is still active.

FIGURE 19–13
Compare Crater Lake in Oregon with the Darwin Caldera.

after the main crater formed. There is a surrounding blanket of pumice and lava ejected from the crater. Geologists have also discovered internal faults around the inner wall.

There is also evidence from the moon that supports the caldera theory. Since the maria are volcanic rock, it would be unusual to find widespread volcanic activity without some sort of craters. In addition, glowing red spots have reportedly been seen in various craters, including Artistarchus. These spots may be active volcanic vents where molten rock reaches the moon's surface.

Arguments can be made against a volcanic origin for all lunar craters. Volcanoes on earth tend to rise up in patterns, such as the "ring of fire" around the Pacific Ocean. (See Figure 11–13.) Lunar craters, however, seem to be dotted randomly over the surface (except for the small chain craters).

Many scientists believe that lunar craters, such as Copernicus are too large to have been volcanoes. At least 72 craters on the moon have diameters over 80 kilometers. No volcanoes of this size are found on earth. The Valles Caldera in New Mexico, one of the largest volcanic earth craters, is only 29 kilometers in diameter. However, larger volcanoes, perhaps 80 kilometers across, may have existed in the past. Some scientists think that ring-like structures of volcanic rock discovered in Africa and Australia are the exposed roots of such large volcanoes.

The alternative theory of lunar craters also has good evidence pro and con. The strongest evidence that lunar craters are formed by the impact of meteorites or comets are the many impact craters on earth. Meteor Crater in Arizona is small compared to many lunar craters. (See Figure 19–14.) If it were on the moon, it would barely be visible through a large telescope. But there are ancient circular structures in Canada as large as 65 kilometers across. (See Figure 19–15.) Many scientists believe that these depressions are the roots of old impact craters.

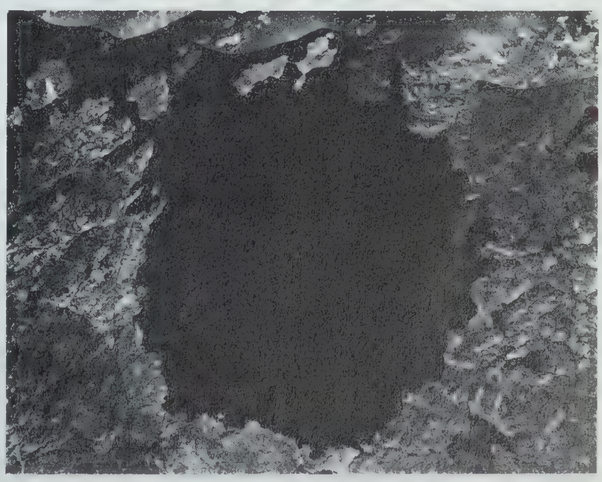


FIGURE 19–14
(left) Meteor Crater in Arizona is one of many impact craters on earth.

FIGURE 19–15
(right) Deep Bay Crater in Northern Canada may be the remains of an ancient impact crater.

A bombardment by meteors would produce a random pattern of craters like the moon's. In addition, lunar craters appear to have been formed by single events. Volcanoes on earth have long histories of alternating periods of eruption and quiet. Finally, many lunar craters look as much like earthly impact craters as calderas. Compare Meteor Crater with Copernicus. (See Figures 19–4 and 19–14.) What similarities do you see? What differences? Can you account for these differences?

Neither theory by itself can explain all the evidence. However, scientists have reached some agreements about the origin of lunar craters. The general opinion is that most lunar landforms were formed by impact. Collisions with meteorites or comets blasted out typical craters like Copernicus. Many scientists favor an impact origin for the circular maria as well, since it is difficult to draw a sharp distinction between the maria and the ray craters.

There are some volcanic craters on the moon. The chain craters fit most of the requirements for volcanic origin. They are small, resemble calderas in appearance, and occur in a regular pattern. Since the return of the Apollo missions, scientists also agree that much of the surface rock (especially in the maria) is volcanic. There must have been extensive volcanic activity after the dark-floored craters and the mare basins were formed. In some cases, impact may have initiated volcanic activity.

Current research shows that rocks altered by the shock of impact can be readily recognized. This new evidence will be useful in determining exactly how lunar features were formed.

Thought and Discussion

1. If you were to land on the moon, what kind of samples would you bring back for analysis?
2. How can your knowledge of landscape processes on earth help you understand the development of lunar landscapes?

FIGURE 19–16
Apollo landing sites.

3. Explain the effect of the water cycle on sculpturing lunar landscapes. How does erosion occur on the moon?
4. The diameter of Copernicus Crater is 92 kilometers, and the diameter of Meteor Crater, Arizona is 1.6 kilometers. Can you find a crater in Figure 19–4 that is the same size as Meteor Crater?

Lunar Research

19–4
Rock samples from the moon

On July 24, 1969 the first samples of rock and soil from the moon were brought back to earth for direct scientific investigation. Before that memorable day, our understanding of the universe was limited mainly to the study of radiation from stars and planets. Until the return of Apollo 11, meteorites were the only objects from outside the earth we could actually hold in our hands. Never before in the history of science have so many hundreds of talented scientists performed so many thousands of tests on samples of rock and soil so rapidly.

Tranquillity Base, the landing site of Apollo 11, is a relatively smooth, level area in the southern part of the Sea of Tranquillity. (See Figure 19–16.) The samples from this site consist of basalt, microbreccias (rocks that are made up of soil and small rock fragments), and lunar soil. The soil is a mixture of crystalline and glassy fragments. It also contains small pieces of iron meteorites. The soil varies in thickness from 3 to 6 meters. The fine grains of soil tend to stick together. This allows the soil to stand as steep slopes. Astronauts found that the clumps of soil crumbled under their boots (Figure 19–17).

Most of the rock fragments are similar in composition to the larger igneous (basalt) rocks

FIGURE 19–17
A footprint in lunar soil.

and were probably formed from them. A small number of crystalline fragments are totally different from the bedrock of the site. They probably came from nearby highlands.

Many of the rocks and fragments in the soil seem to have been eroded by high velocity impacts. The glassy fragments contain beautifully preserved microscopic pits caused by the impact of tiny particles (Figure 19–18).

Near the spot where the lunar module landed, the surface is pockmarked by craters. They range in diameter from less than 2 centimeters to several tens of meters. Some have sharply raised rims and shallow flat floors or floors with central bumps. (See Figure 19–19.)

The lunar surface at the Tranquillity Base site is composed of loose material ranging in size from particles too fine to be seen with the naked eye to blocks more than a meter across.

19–5
Origin of the moon

Scientists have proposed many theories of lunar origin. Some scientists thought that the moon broke away from the earth very early in their mutual history. Others thought that the moon had been "captured" by the earth's gravitational field.

The analysis of moon rocks provides evidence that the moon was never a part of the earth. The moon rocks gathered so far have a chemical composition very different from that of the sun or the earth. Moon rocks have higher titanium, chromium, and zirconium contents than earth rocks or the sun's atmosphere. Other elements such as nickel, sodium, potassium, and europium are much less abundant. The ratio of iron to nickel in the moon is larger than the ratio of iron to nickel in any other known sample of cosmic matter. Common earth elements such as carbon and nitrogen have not yet been found in the lunar crust.

Scientists now believe that the moon probably formed by the accumulation of dust particles. However, they don't know whether this accumulation occurred within the earth's field of gravity. One theory suggests that the moon formed from particles orbiting the earth in Saturn-like rings over 4.6 billion years ago. An-

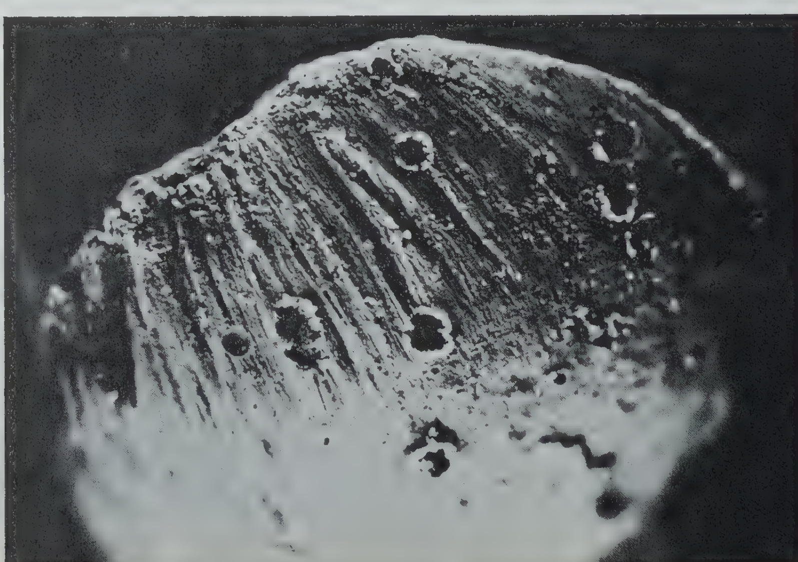


Figure 19–18
A closeup of a lunar rock that has been bombarded by tiny meteorites.

other idea is that the moon formed outside of the earth's field of gravity and has since been "captured" by the earth.

19–6
Age of the moon

One of the most important scientific results of the Apollo missions is the determination of the age of lunar rocks. This information can help scientists unravel the history of the earth-moon pair. The rocks collected by Apollo 11 from the Sea of Tranquillity crystallized some 3–4 billion years ago. Those collected by Apollo 12 from the Ocean of Storms gave age determinations of 2–3 billion years. This range in age indicates that not all parts of the surface of the moon solidified at the same time.

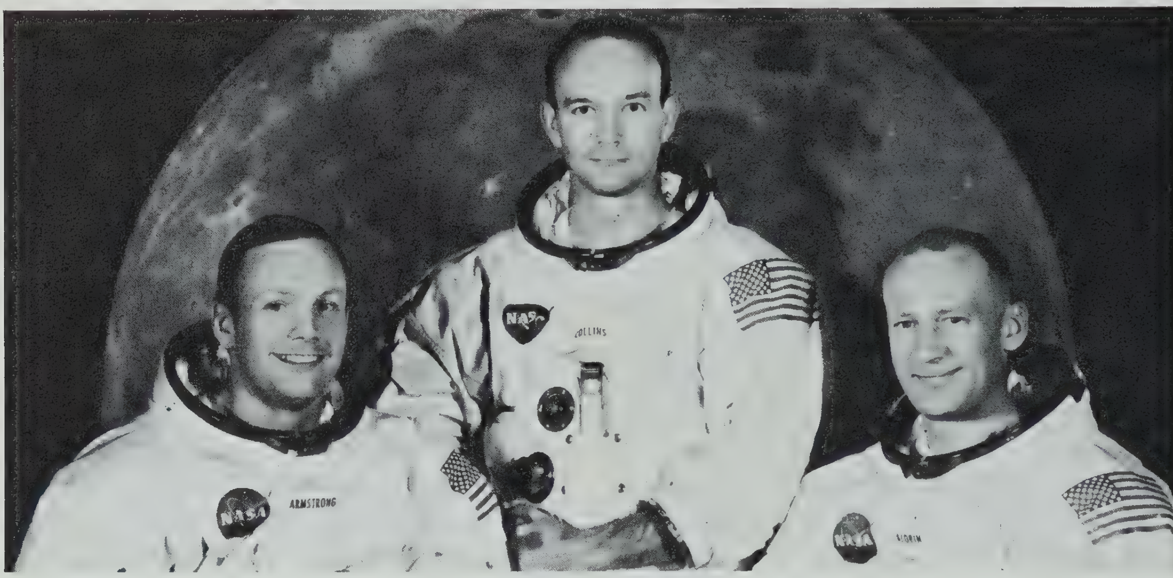
Scientists were also surprised that on each landing site the soil was older than the larger blocks of rock. The finer materials have an average age of around 4.6 billion years. (This is also the age of the oldest known meteoritic material.) The light color of these small chips suggests that they were blasted out of the highland regions by meteorite impact. In any case, solid matter existed on the moon's surface 4.6 billion years ago. The younger rocks of the dark lunar mare were produced by isolated meteorite impacts or volcanic activity long after the formation of the moon.

19–7
"Lost on the moon"

Imagine that you belong to a space crew. You are scheduled to rendezvous with a mother ship on the lighted surface of the moon. However, mechanical failures forced your ship to crash-land 200 miles from the rendezvous point. The

Figure 19–19
The lunar surface near the landing site of Apollo 11.

APOLLO 11 ASTRONAUTS:
Man on the moon



On July 16, 1969 the Apollo 11 rocket blasted off from Cape Kennedy, carrying astronauts Edwin Aldrin, Jr., Neil Armstrong, and Michael Collins on their historic journey to the moon. All three men were former test pilots and space flight veterans.

On July 19 the spacecraft went into orbit around the moon. While Collins remained at the controls of the command module *Columbia*, Armstrong and Aldrin entered the lunar landing module *Eagle*. The two modules separated, and *Eagle* flew down to the moon, landing in the Sea of Tranquillity.

The men had to spend time adjusting their bulky suits. Each suit was a miniature environment. It contained water, oxygen, electricity, refrigeration, and two-way radios. Six and a half hours after landing, they were ready for their walk on the moon:

> . . . Armstrong steps off the ladder, very carefully, and his booted foot touches the lunar surface. The rubble and the rocky moonscape seem familiar—they were simulated in his training program. The intense light and the blackness of the shadows are no longer strange.
>
> He moves away from the ladder and the odd-looking craft standing with metallic legs a-straddle, and turns slowly for a look around his limited horizon. A fast-moving, bright satellite swings into view, lifting rapidly above the horizon and toward the zenith. But this time the satellite is no longer a projected image on the dome of a simulator. It's an orbiting spacecraft, standing by. The intense light is the sun, not arc lights. And the rubble under his boots is truly the surface of the moon.
>
> David Anderton, NASA

rough landing damaged much of the equipment aboard.

Survival depends on reaching the mother ship. Below are listed the 15 items left intact after landing. Your task is to rank them in terms of their importance to your crew in its attempt to reach the rendezvous point 200 miles away. Place number 1 by the most important item, number 2 by the second most important, and so on through number 15, the least important.

_____ *Food concentrate*
_____ *50 feet of nylon rope*
_____ *Parachute silk*
_____ *Portable heating unit*
_____ *Two .45 calibre pistols*
_____ *One case dehydrated milk*
_____ *Star map*
_____ *Life raft*
_____ *Magnetic compass*
_____ *Signal flares*
_____ *First aid kit containing injection needles*
_____ *Solar powered FM receiver-transmitter*
_____ *Two 100-pound tanks of oxygen*
_____ *Box of matches*
_____ *Five gallons of water*

Thought and Discussion

1. Try to find out what kinds of tests scientists are performing on the samples of rock and soil from the moon.
2. The device invented to monitor the heartbeats of astronauts is now being used to detect future victims of heart attacks. What other devices originally designed for the space program are now being used here on earth?
3. Why did scientists want to know the age of the moon?

Unsolved Problems

Information gathered from the Apollo moon missions is helping scientists to solve an important question: is the moon divided into layers like the earth? The moon might have

Figure 19–20 *The Lunar Rover of Apollo 15 on the surface of the moon.*

been originally composed of molten material that has been slowly cooling throughout geologic time. In that case, scientists would expect many layers to form. As a melt cools, the heavier rocks crystallize first and sink to the bottom of the melt. The lightest rocks are the last to crystallize. They would float to the top of the melt. Rocks of intermediate composition would settle in the middle.

If the moon were originally a "melt," scientists would expect to find the lightest rocks on the tops of the high mountains. The heavier rocks should be in crater floors. **Anorthosite,** a very light rock, was found in the Apennine Mountain region during the Apollo 15 mission. Heavier rocks were found at the base of the mountains. This evidence, along with information recorded on lunar seismographs, seems to indicate that the moon was once hot and that it has since been divided into layers. However, more data is needed before scientists can describe the history of the moon with any certainty.

Chapter Review

Summary

The moon has two main types of landscapes: the relatively smooth, dark maria and the heavily cratered highlands. The chief features on the moon are craters. Typical craters have a rim, a series of terraces, and an ejecta blanket. Some craters also have rays. Smaller topographic features include the mare ridges, rilles, chain craters, and domes.

The origin of the mare basins is still uncertain. The mare material itself is lava that has been reduced to rubble by the bombardment of meteorites. Scientists generally agree that most craters were formed by impact. The smaller chain craters probably are volcanoes.

Even though men have landed on the moon, the origin of the moon is still uncertain. The moon rocks have a different chemical content from that of the earth's crust. It is therefore unlikely that the moon was ever a part of the earth. Scientists now believe that the moon probably formed from dust particles.

Landscapes on earth result from the interaction of the water cycle and rock cycle. Without an atmosphere there would be no water cycle. In its absence, sedimentary rocks would be scarce or nonexistent. There would be no geosynclines, no Grand Canyon, and perhaps no continents. Igneous rocks might have different compositions. Probably there would be no life on an earth without an atmosphere.

These are speculations because the earth *does* have an atmosphere. But the moon in effect furnishes a laboratory for studying the evolution of a planet that has no air and no water. For this reason, scientists feel that lunar exploration will also reveal much about the earth. In addition it will satisfy man's curiosity. There is now a wealth of photographs of the moon taken by unmanned satellites. Most important, with the advent of manned landings on the moon, scientists have an exceptional opportunity to explore and study the moon and thus to learn about our earth.

Questions and Problems

A

1. How do the moon's seas differ in appearance from the highland areas?
2. What processes that help shape the earth's surface are also active on the moon?
3. What processes that help shape the earth's surface are not active on the moon?

B

1. What is the most widely accepted theory of the origin of the moon?
2. Why is there no water on the moon's surface?
3. Why would the moon make an excellent platform for astronomical observations?
4. What does a seismograph placed on the moon's surface tell you about the moon's interior?
5. Can you tell relative ages of some of the lunar features by simple telescopic observation? How?

C

1. Outline the volcanic theory of lunar crater origin, discussing its weak and strong points.
2. Outline the impact theory of lunar crater origin, discussing its weak and strong points.
3. What are some of the effects of the moon's low gravitational force?
4. Discuss in some detail several reasons why man wanted to journey to the moon.
5. If you were a scientist studying the moon, what experiments would you have astronauts perform on the surface of the moon? What would you hope to learn from these experiments?

Suggested Readings

Books

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Hess, Wilmot, Kovach, Robert, Gast, Paul W., and Simmons, Gene, "The Exploration of the Moon." *Scientific American*, October, 1969.

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20. The Solar System

Because the planet earth is our home, it is an important part of the solar system. But it is only one of nine known planets in the system. Some of the other planets are much bigger than the earth. Jupiter alone could hold 1,300 earths inside it.

Our moon is a member of the solar system, too, along with 31 known moons that circle other planets. Comets and meteors also belong. All these objects travel in orbits around the sun, which occupies a central position.

The sun controls this solar system through the force of gravitation. All the members of the sun's system, from huge Jupiter to tiny particles in space, move with mathematical precision day after day, year after year. The positions of the planets in the sky, the rising and setting of the sun and moon, eclipses, and other celestial events can be accurately predicted years, even centuries, in advance.

The solar system has often been compared to a gigantic and exact clockwork. It contains more moving parts than any ordinary clockwork. At the great observatories of the world, standard clocks are set by observing the motion of the celestial clock whose "hands" are the sun, moon, and planets. When we set our watches by a radio time signal, we are really setting them to match the sky-clock.

The solar system resembles a watch in still another way. Its main working parts operate in a thin disk. However, this disk is far thinner in proportion to its diameter than the thinnest watch. Unlike a watch, the parts of the solar system are far apart from each other in comparison to their size.

Motions of the Planets

20–1 Investigating interplanetary distances

To help you visualize the great distances between planets, make a scale model of the solar system. Then you may better understand the problems that face the astronomer and the astronaut in their exploration of space.

Procedure

The average distance from the earth to the sun is called one ***astronomical unit.*** *(1 A.U.) The average distance of all the planets from the sun is given in Figure 20–1. The diameter of the earth is roughly one ten-thousandth of an astronomical unit. If you choose a meter to represent 1 A.U., then the earth will be a speck about 0.1 millimeter in diameter. If you want the earth to be easily visible on your model, you must make your unit for the astronomical unit larger in the same proportion. If the earth is to be one millimeter in size, the A.U. must be ten meters. This will give you an uncomfortably large model.*

The sizes of the planets compared to the earth are also given in Figure 20–1. Thus, whatever size you choose for the earth, Jupiter will be 11 times larger.

Choose a unit to represent one astronomical unit that you feel you can handle. After you have chosen your unit, make a table of distances and diameters. If your A.U. is one meter, then your table should show that Jupiter is 5.2 meters from the sun (in your model) and about one millimeter in size.

After you finish the table, plot the values for distance on a long piece of paper (a roll of adding machine paper will work well). Or you may build your model in a large room (the gymnasium will do) or on the playground. Use toothpicks placed in the ground to represent the positions of the planets.

Now that you have constructed your model, you can see that the solar system is mostly space!

Suppose you wanted to include the nearest star to the sun in your model. We know that

Figure 20–1
Planetary Distances from Sun, Planet Diameters, and Planet Masses

Planet	Distance in A.U.	Diameter (*Earth* = 1)	Mass (*Earth* = 1)
MERCURY	0.4	0.4	0.05
VENUS	0.7	1.0	0.82
EARTH	1.0	1.0	1.0
MARS	1.5	0.5	0.1
JUPITER	5.2	11.2	318.3
SATURN	9.5	9.5	95.3
URANUS	19.2	3.7	14.6
NEPTUNE	30.1	3.5	17.3
PLUTO	39.5	1?	0.9
SUN		110	333,420
Nearest star to sun	270,000	100	300,000

this star is 270,000 A.U. away. Figure out where you would have to put another centimeter-sized ball (about the size of a marble) to represent this star.

20–2 How we learned about the solar system

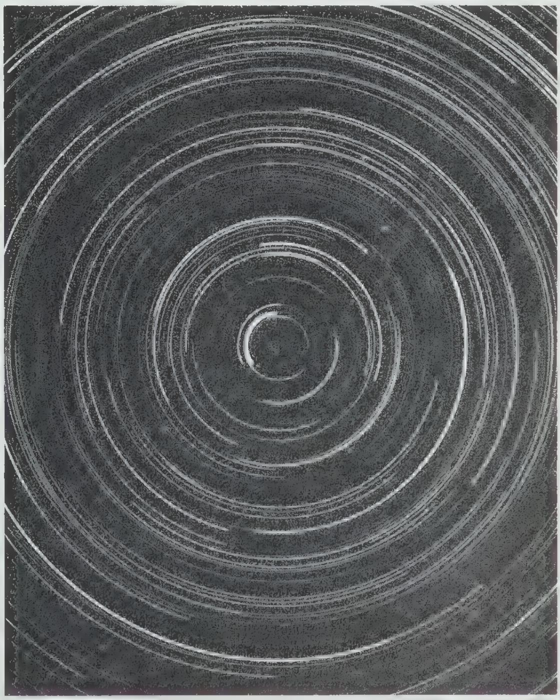
There is evidence that our solar system has been here for more than four billion years. Man has been on the planet earth for two to three million years. His understanding of the solar system, however, began scarcely 300 years ago.

The ancients tried to explain what they saw happening in the sky. They failed because of a serious but natural error. They thought the earth was standing still at the center of the universe, and that the sun, moon, and stars all revolved around the earth.

The sun and moon *appear* to move across the sky from east to west: setting in the west and rising again in the east the next day. And the stars that form our familiar constellations —the Big Dipper, Orion and many others— certainly seem to travel around the earth each day. We now know that the earth's turning makes the sun and stars appear to travel around us (Figure 20–2). The ancients could not believe that the solid earth, the center of their universe, could be moving. So they had to invent an imaginary scheme to make the stars go around.

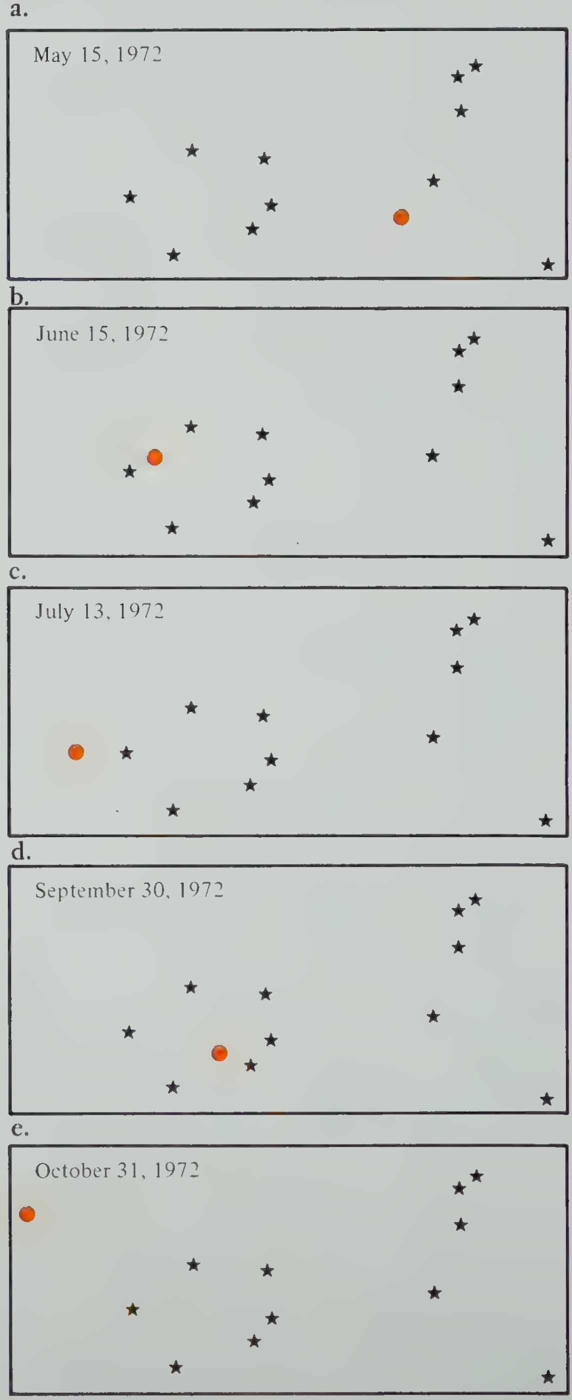
To add to the difficulty, a few "stars" in the sky did not behave like the others. Because they wandered among the other stars, they were called "planeta," which means "wanderers." The planets do seem to move among the stars in a strange, puzzling way. Mars, for example, will move eastward *among the stars* night after night. Then it slows down, stops, and goes in the opposite direction. After a time it again slows down, stops, and then resumes its regular eastward motion among the stars. No wonder the ancients were puzzled.

FIGURE 20–2
This is a long-exposure photograph of the sky above the North Pole. The star trails are produced by the earth's rotation.



ACTION *The positions of Mars in the sky from May through October 1972 are shown on the sky maps in Figure 20–3. Place a piece of tracing paper over Figure 20–3a and mark the position of the stars and of Mars. Then place the tracing paper in turn exactly over b, c, d, and e by matching the stars. Mark the successive positions of Mars and connect them by a line. This line is the apparent path of Mars among the stars during those months.*

FIGURE 20–3
Simplified sky maps show the motion of Mars among the stars.



The Greek astronomer Ptolemy around 140 A.D. proposed a scheme to explain these puzzling motions. He used it to predict future positions of the planets. His system is indicated in Figure 20–4.

All astronomers since classical time had agreed that celestial motions were circular. The backward motion of the planets was explained in Ptolemy's scheme by assuming that each planet moved on a small circle, called an "epicycle." The center of that small circle, in turn, moved on a much larger circle around the earth. Mars is shown here in the "backing up" position in its orbit.

For about 1,400 years the Ptolemaic theory was accepted. But new generations of thinkers grew dissatisfied with his scheme. It was very complicated and predicted the positions of the planets poorly. Copernicus (1473–1543) was one of the men who sought a simplified system. He proposed a shocking idea: that the earth moved around the sun. Now the *apparent* backward motion of the planets could be easily

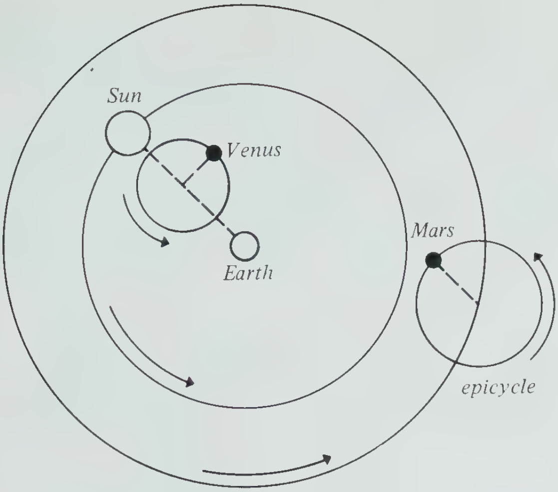
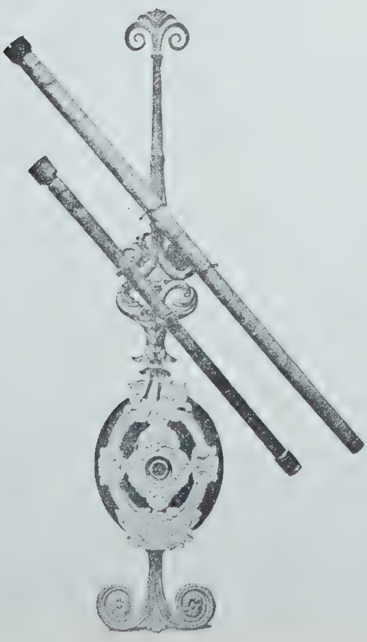


Figure 20–4
The planetary system proposed by Ptolemy.

Figure 20–5
Galileo's telescopes are now in a museum in Florence, Italy.



explained. In its journey around the sun the faster-moving earth passes the slower-moving Mars. Mars appears to move backward, just as a slower moving train seems to move backward when you pass it on a faster train.

Copernicus could not prove that the earth really moved. The invention of the telescope made such proof possible. It not only ended the long reign of Ptolemy's theory, but also led to a totally new concept of the universe. We do not know for certain who invented the telescope, or when. We do know that Galileo constructed several small telescopes (Figure 20–5). One great discovery followed another as Galileo turned his telescope to the sun, moon, and the planets.

20–3 Motions and phases of Planet X

In 1610 Galileo reported that a certain planet had a full cycle of phases just like the moon. At full phase this planet appeared only one-sixth as large as in its new phase. Galileo knew that these observations refuted Ptolemy's theory. But like other scientists of his era, he was afraid to announce his scientific results openly for fear of imprisonment or something worse. So he announced his discovery in the form of an anagram. When decoded it read: "The Mother of Loves imitates the forms of Cynthia." After you finish this exercise, you will find out what Galileo meant by this message.

Procedure

The photographs in Figure 20–6 represent what Galileo saw through his telescope. Remember that the object you are viewing (Planet X) is a planet slowly changing its position among the stars and its phases, night after night.

First construct a simple model as in Figure 20–7. The light bulb represents the sun. The ball on a stick represents Planet X, and you are the observer on earth. Try to make the ball look like Planet X in the photos. It will be easier to see the phases if the room is darkened so that the ball is illuminated only by the light bulb.

Where does the ball have to be relative to the earth and the sun and how must it move to be able to show all the phases of the moon?

After you have examined all the possible relationships between Planet X and the "sun," answer the following questions:

1. What planet do you believe Planet X represents?
2. Is the orbit of Planet X in the same plane as the earth's orbit? How do you know?
3. Are the phases of the moon and of Planet X caused in the same manner?
4. If Ptolemy's scheme were correct, could Planet X show all the phases of the moon?

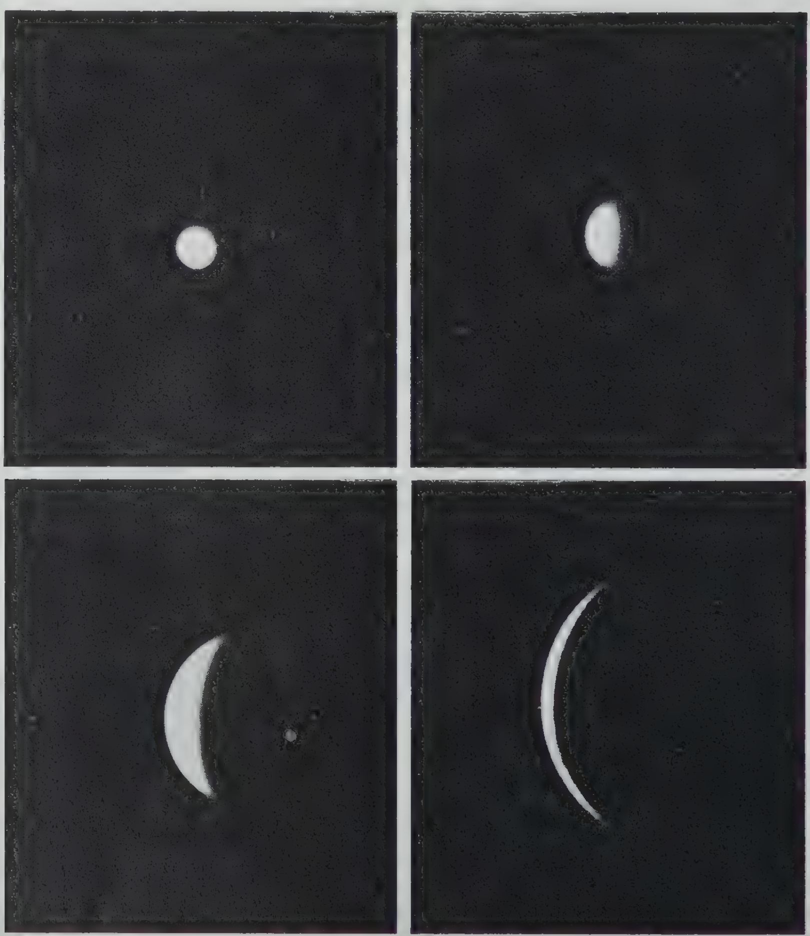


Figure 20–6
Phases of planet X.

20–4 The mechanics of the solar system

Galileo's telescope also showed that Jupiter had four large moons. Jupiter was a miniature solar system in itself. It was therefore easier to believe that the earth was a planet circling the sun.

These discoveries did not solve all the problems. Why did the planets go around the sun and what sort of paths (orbits) did they follow? Why did Venus move faster than the earth, and Mars more slowly? The answers to these questions came in steps. One great scientist after another provided the clues. The German astronomer, Kepler, used the precise observations of the Danish astronomer, Tycho Brahe. Following traditional beliefs, Kepler thought that circles were "perfect curves." Therefore, heavenly bodies would naturally follow circular paths. But using circles led to minor errors in predicting planetary positions. Kepler's stubborn refusal to accept these errors finally led to his discovery of the real shape of the orbits.

Kepler announced the first two of his laws of planetary motion in 1609. The third followed ten years later. Kepler's first law is this: *planets move about the sun on ellipses.* The second law tells us how they move on these paths. *Each planet moves in such a way that a line joining the planet to the sun passes over equal areas of space in equal times.* This relationship is shown in Figure 20–8.

The second law explains why the earth moves faster in winter than in summer. In winter in the Northern Hemisphere, the earth is closer to A and swings around the sun faster. It is for this reason that there are fewer days between

FIGURE 20–7

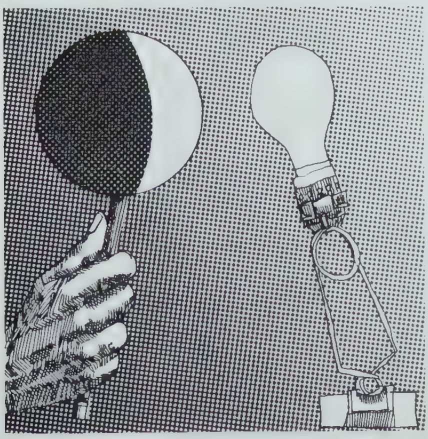
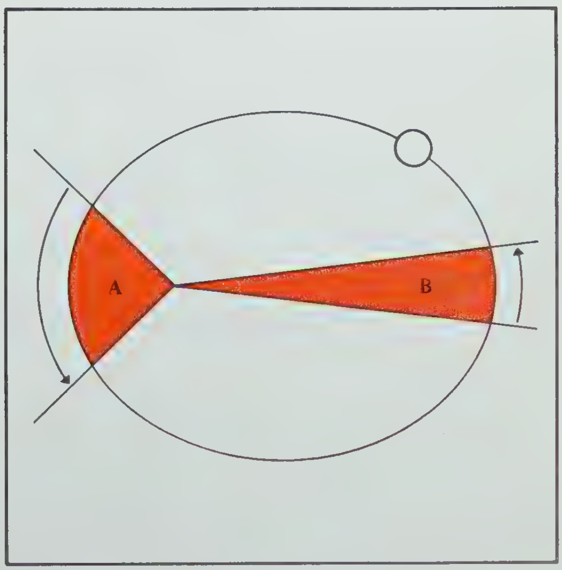


FIGURE 20–8
Kepler's second law. Area A is equal to Area B.



GALILEO GALILEI

While attending services at the Cathedral of Pisa, Galileo (1564–1642) timed a swinging chandelier with his pulse. This led to his discovery that the swing of a pendulum depends on its length not on the extent of its swing.

Galileo was a Renaissance genius whose ideas changed the direction of scientific thought. His scientific observations led scientists away from the limited views of Aristotle and prepared the way for Newton.

Galileo started the science of dynamics through his studies of falling objects. A famous legend tells of Galileo's dramatic demonstration of dropping two cannonballs of unequal weight from the Tower of Pisa. Both landed at the same time. This showed that all objects fall at the same rate regardless of weight. It contradicted Aristotle's idea that the rate of fall of an object was proportional to its weight.

In 1609 Galileo built his own telescope and began to study the stars and planets. He described the mountains on the moon's surface, the myriad stars in the Milky Way, the satellites of Jupiter, and the phases of Venus. He used the changing location of sun spots to show that the sun rotated on its axis in 25 days.

Galileo's telescopic discoveries convinced him of the Copernican theory of the solar system, that the sun was the center of the universe. But the church in Italy favored Ptolemy's idea, that the earth was the center of the universe. The Church declared Copernicanism a heresy in 1616. Galileo was forbidden to teach his views.

In 1632 with a different Pope in the Vatican, Galileo chanced a publication of his masterpiece *Dialogue on the Two Chief World Systems.* He was brought before the Inquisition and forced to renounce his views. Nevertheless, Galileo's work was already established. The Copernican idea of the solar system prevailed.

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autumn and spring than there are between spring and autumn.

Next, Kepler was curious about how one planet's orbit was related to another. He knew that the time required for planets to go around the sun (the period of the planet) increased with their distance from the sun. Kepler found that *the square of the periods of the planets have the same ratios as the cubes of their distances from the sun.* This is his famous third

law. If the *p*eriod of the planet is measured in earth years, and the *d*istance of the planet from the sun is measured in astronomical units, then $p^2 = d^3$.

Does it work? The period of Mars is 1.88 years. Square it: $1.88 \times 1.88 = 3.54$. The distance of Mars from the sun, on the average, is 1.52 times the earth's distance. Cube it: $1.52 \times 1.52 \times 1.52 = 3.54$.

Test the third law for yourself on some other planet, for instance, Jupiter. The period of Jupiter is 11.86 years, and its distance is 5.20 astronomical units.

Kepler's laws described how the planets moved. But he did not know *why* they moved in this way. It was Sir Isaac Newton who showed that the orbits of the planets were controlled by gravity. But until we know what gravity *really* is, we still won't know why the planets move as they do. This is true of science in general. The basic nature of matter and energy still eludes us. Whatever gravitation really is, it is the force—the mainspring—of the solar system clockwork.

Thought and Discussion

1. Why do you think it was so difficult for the ancients to think of the earth as moving—turning on its axis and circling the sun?
2. One argument against the turning of the earth was the following. If the earth turns, you should land in a different spot when you jump up off the ground. Why is this argument false?
3. The retrograde (backing up) motion of the planets was a big puzzle to the ancients. Can you give some examples of retrograde motion one can experience here on earth?
4. Can you think of other ways in which the solar system resembles a clockwork?

The Sun's Family

20–5 Tools for studying the solar system

Newton discovered the law of gravitation nearly 300 years ago. The science that uses this law to predict the exact motions of all members of the solar system is called **celestial mechanics.** The same science applies to communications satellites and space probes that man has put into the skies. The course of an astronaut from the time he leaves the launching pad at Cape Kennedy until he lands at a chosen spot on the moon can be precisely calculated. The space age is made possible by computers performing the painstaking calculations.

Until recently, man could only look passively at the planets through his land-based telescopes. And he was forced to look from the bottom of a huge ocean of atmosphere. It blurred the image and prevented high magnification.

New means of exploration are now available, both in space and on earth. Radio waves are not affected as much as light waves by passage through our atmosphere. Both radio and radar telescopes have become important tools in solar

system exploration (Figure 20–9). Radio telescopes "listen" for radio waves generated by a celestial object itself. Jupiter, for example, is a source of radio waves. Radar telescopes can also aim radio pulses at a planet and receive the return waves that have bounced off the planet. A radar map of Venus is shown in Figure 20–10.

There is something more important than all the new instruments that man can use on earth. He can now send his telescopes and himself *above* the interfering atmosphere to get a clear view of the skies. This view includes the ultraviolet rays and x rays that do not penetrate our atmosphere. Someday man may send spaceships to all of the planets. At first, they will only carry instruments. But man will certainly travel to some of these other worlds himself.

Close-up views of the planets once only imagined in science fiction stories, have be-

FIGURE 20–9
This telescope is designed to receive radio waves from outer space.

FIGURE 20–10
The cloud-covered surface of Venus can be mapped by radar, which penetrates the clouds.

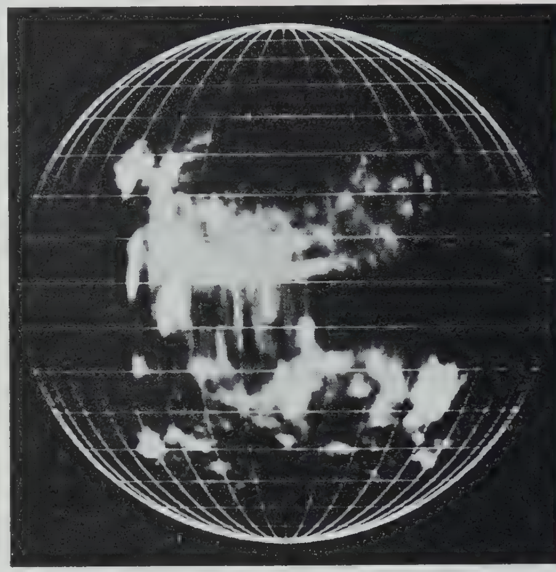
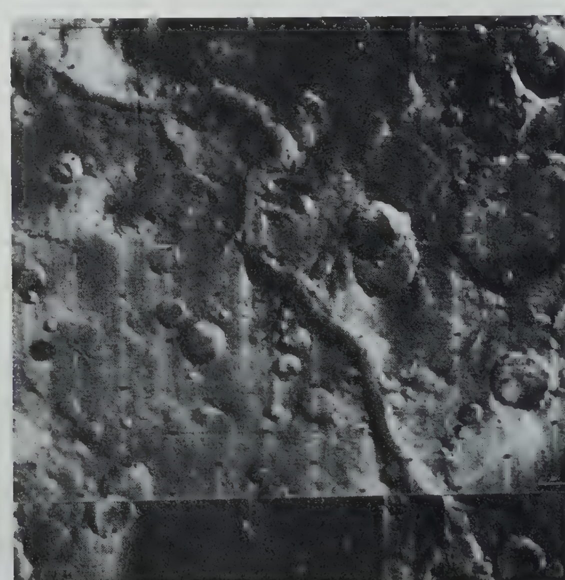


FIGURE 20–11
What does a close-up photo of Mars reveal about the planet that even the best photographs from earth cannot?



come reality in the case of Mars and Venus. Compare a good photograph of Mars taken through a telescope and one taken by a Mariner space probe and sent back to earth by television (Figure 20–11). These close-up views raise more questions about conditions on the planets than they answer. They provide exciting new data for solar system research.

20–6 Two types of planets

Although they differ greatly from each other, the planets can be divided into two main groups: the terrestrial (earthlike) planets and the major, or giant planets. The first are closer to the sun (Mercury, Venus, earth, and Mars). They are comparatively small in size and mass. Pluto is also in this terrestrial group. But it is an exception as far as distance is concerned. The major planets are all giants and very massive: Jupiter, Saturn, Uranus, and Neptune.

The mass of a planet and its distance from the sun determine its chemistry and, therefore, its ability to support life. The massive planets have a strong gravitational pull. They held on to light gases like hydrogen and helium after they were formed. Hydrogen and helium are the most abundant chemical elements in the universe. Hydrogen combines easily with carbon and nitrogen to form methane (CH_4) and ammonia (NH_3). There are large amounts of these noxious gases in the atmospheres of Jupiter and Saturn.

The terrestrial planets were not gravitationally strong enough to retain large amounts of hydrogen and helium. (Most of the earth's hydrogen is bound to oxygen in the form of water.) The atmospheres of the small planets are less extensive. Mars has a thin atmosphere and Mercury no atmosphere at all. It is too small to keep gases from escaping into space.

FIGURE 20–12
Planetary Data

	PERIOD OF REVOLUTION AROUND SUN	PERIOD OF ROTATION ON AXIS	NUMBER OF MOONS	DENSITY (Water = 1.0)
MERCURY	88 DAYS	59 DAYS	0	5
VENUS	225 DAYS	243 DAYS	0	5⅓
EARTH	365 DAYS	1 DAY	1	5½
MARS	687 DAYS	1.03 DAYS	2	4
JUPITER	12 YEARS	9.9 HOURS	12	1⅓
SATURN	29½ YEARS	10.2 HOURS	10	¾
URANUS	84 YEARS	10.8 HOURS	5	1½
NEPTUNE	164 YEARS	15.8 HOURS	2	2
PLUTO	247 YEARS	6.4 HOURS	0	?

Because the massive planets are rich in the light elements, they are much less dense than the earthlike planets. (Saturn is so light that if one had a tub large enough it would float!) The terrestrial planets have a greater share of the heavier elements, and are thus denser. The earth is the densest of all the planets.

20–7 The terrestrial planets

MERCURY Tiny Mercury, not much larger than our moon, is the smallest planet and the one closest to the sun. It races around the sun in just 88 days. Because Mercury is near the sun, it is difficult for us to see it in the sky. When it is farthest from the sun as viewed from earth, it can be seen just after sunset or just before sunrise. It looks like a brilliant star. Like Venus, it shows the full set of phases. Mercury rotates on its axis more slowly than the earth does. It takes 59 earth days for one rotation. It has no moons, and its surface is probably pockmarked and barren like our own airless moon's. It receives ten times as much light and heat from the sun as we do, and must be a very well-baked planet indeed.

VENUS Of all the planets, Venus, is most nearly like the earth in mass and size. But there are important differences. Venus has a perpetually cloudy atmosphere composed of great quantities of carbon dioxide and dust. The surface of Venus is much hotter than the earth's, probably as high as 600°C. That's hot enough to melt lead. This high temperature results not only from Venus's closeness to the sun, but also from the carbon dioxide that keeps heat from escaping from the surface.

Venus shows phases, as Galileo discovered. Like Mercury, it never appears too far from the sun in the sky. Since Venus is farther from the sun than Mercury, it remains much longer as a bright object in the evening sky. It is the most famous of the "evening stars." When Venus is in a different part of its orbit, it is a brilliant "morning star," rising before the sun.

Like Mercury, Venus does not have any moons.

Radio and radar measurements have shown that both Venus and Mercury rotate very slowly on their axes. Mercury takes 59 days to turn about once and Venus 243 days. Calendar makers on Mercury would have a weird task. There would be only one complete day in a year, which is 88 of our days long.

The calendar makers on Venus wouldn't be much better off. The year there would be about two days long (Figure 20–13). Incidentally, Venus rotates "backwards," opposite to the way the other planets rotate.

EARTH An observer from space would call us a blue-white planet with a large, pale yellow companion, our moon. Our moon is larger compared to its planet than any other moon in the solar system. (The earth-moon system could be called a double planet.) Seasonal changes on the earth would be visible from space. But signs of life would be extremely hard to detect.

MARS Mars is half the size of the earth and one-ninth as massive. It spins on its axis at

FIGURE 20–13
For the observer on Venus, it is noon at point A. Approximately what time of day is it at points B, C, and D? The dashed line shows that Venus and the observer return to point A just before the start of the second day.

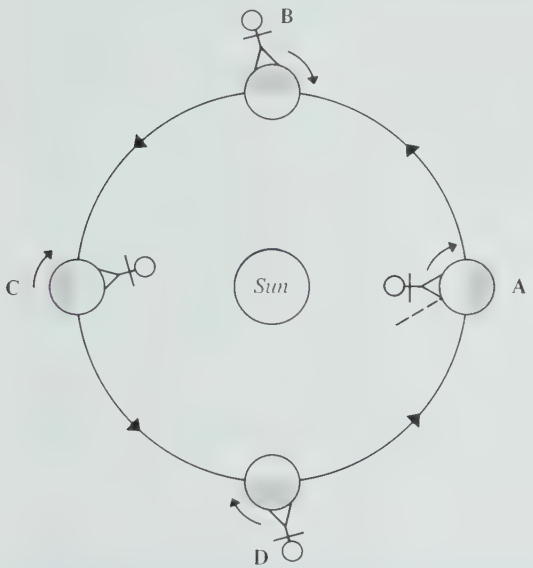


FIGURE 20–14
Phobos is one of Mars' two tiny moons.

almost the same rate as the earth. This gives it a rapid succession of days and nights. Once it was thought that the "canals" on Mars (fine straight markings extending from the poles toward the equator) were a sign of life. It was imagined that an older civilization had constructed these canals. They were thought to be huge irrigation ditches to guide water from the melting polar caps. We now believe that these caps are frozen carbon dioxide.

It was exciting to think of a civilization, similar but more advanced than ours, living on the next world outward from the sun. But the Mariner probes found no evidence of actual canals. They did find many markings suggestive of water erosion in the distant past.

The atmosphere of Mars is extremely thin. There is only a trace of free water. The daytime temperatures on Mars rarely reach 80°F, even at the equator. Yet a trace of water and a thin atmosphere may still support life. Perhaps this life, if it does exist is only single-celled animals and plants. Mariner probes are scheduled to land during the next few years. If they find even simple life forms, it will be an important discovery. It would destroy the concept that life on earth is a rare accident. It would mean that life is probably a natural occurrence, wherever conditions are favorable.

Mars has two tiny moons, Phobos and Deimos. Through a powerful telescope on earth they are visible only as tiny specks of light. From the Mariner 9 photographs, even small craters on their rocky surfaces could be counted (Figure 20–14). Both moons are only a few miles in diameter and thus very tiny compared to their central planet.

Pluto From Pluto, the outermost of all the planets, the sun would only appear as a very bright star. Pluto takes 247 years to circle the sun, from which it receives very little light and heat. Its landscape must be one of utter barrenness, gloom, and cold. Pluto has no known moons.

20–8 The major planets

Jupiter The largest of the giant planets is Jupiter. It is more than 300 times as massive as the earth and 11 times its diameter. Despite its size, it rotates on its axis in less than 10 hours. Jupiter is turning so rapidly at the equator (26,000 miles per hour) that it bulges outward. Because the atmosphere rotates faster near the equator than at higher latitudes, it shows marked bands (Figure 20–15).

Jupiter has 12 known moons. Four of them are large enough to view with a good pair of binoculars. One of these moons, Ganymede, is larger than the planet Mercury. Another, Callisto, is larger than the earth's moon. But compared to Jupiter they are small.

As Jupiter circles the sun every 12 years, it receives 25 times less heat and light than we do from the sun. Yet Jupiter is far from cold. Underneath its dense atmosphere of ammonia, methane, and hydrogen it is possible that it has a temperate zone. Conditions for life might exist there.

Data radioed from a rocket known as Pioneer 10 is expected to provide more information on Jupiter. Pioneer 10 will pass 135,000 kilometers from the surface of Jupiter on December 3, 1973. At that time it will take radio signals 45 minutes to reach from Jupiter to the earth. In the 1980's Pioneer 10 will pass into

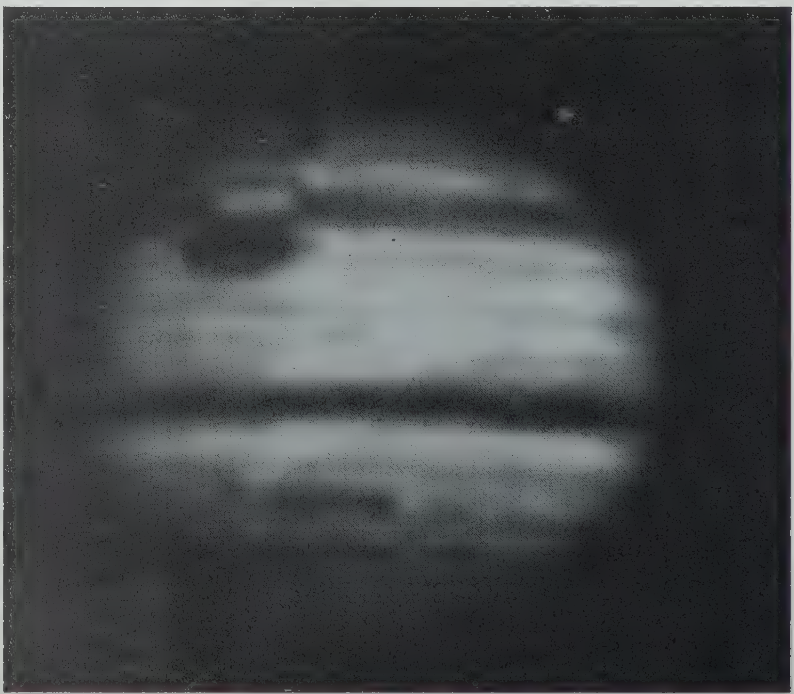


Figure 20–15
The giant planet, Jupiter, with its broad atmospheric bands. The large spot in the northern hemisphere is red; no one knows what it is. The small dark circle is the shadow cast by Ganymede, located to the right of the planet.

the space beyond the solar system, to wander there for millions of years. Pioneer 10 carries a plaque which tells the story of its origin. Perhaps in millions of years it will be intercepted by another civilization.

SATURN Saturn and its rings form one of the showpieces of the solar system (Figure 20–16). The rings are extremely thin, vast belts of tiny "moonlets." They may be the remains of a crushed moon that came too close to Saturn and was destroyed by strong tidal forces. Or they may be material that never could form into a moon because it was too close to Saturn. Saturn also has ten moons that lie outside the tidal force "danger zone." They make up a small "solar system." Saturn takes 29 years to travel once around the sun.

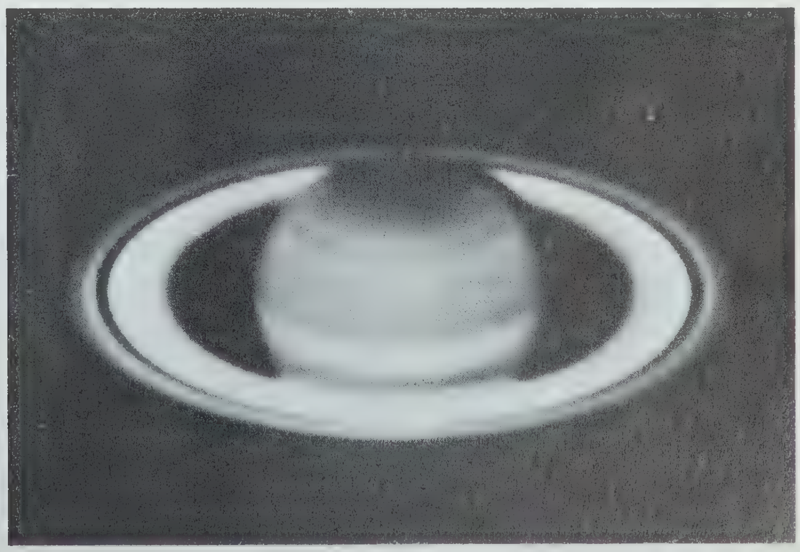
URANUS This planet, which takes 84 years to circle the sun, was discovered by Sir William Herschel in 1781. All those planets lying closer to the sun had been known from antiquity. On a clear dark night Uranus can be seen as a tiny star, but a telescope is necessary for a clear view. It appears as a faint green disk. Its color probably comes from dense clouds of methane in its atmosphere.

NEPTUNE Neptune is a twin of Uranus that is nearly a billion miles farther from the sun and is therefore much colder. This tiny green disk can only be seen with a telescope as it slowly changes its position among the stars.

ACTION *Many newspapers and magazines announce from time to time which planets are evening and morning "stars." Your local library has copies of almanacs and yearbooks. They give this information, along with the phases of the moon and other astronomical data. Your school library probably has a World Almanac.*

Find out when Venus, Mars, Jupiter, or Saturn will be evening stars. Locate them in the sky. When Venus is an evening star, it is the brightest object in the western sky after sunset. It is impossible to miss. When Mars, Jupiter,

FIGURE 20–16
Saturn and its rings.



or Saturn are evening stars, they are brightest when rising in the east just after sunset.

Watch your chosen planet twice a week for at least two months. Plot its position among the stars. If possible, view it through a telescope. Try to observe the phases of Venus, the moons of Jupiter, and the rings of Saturn.

20–9 Asteroids

When you made a model of the solar system in Investigation 20–1, you probably noticed a large gap between the orbits of Mars and Jupiter. For years astronomers searched for a "lost" planet to fill the gap. Then, especially with the aid of photography, they discovered thousands of them! These tiny planets are called **asteroids.** The largest, Ceres, is only 480 miles in diameter. One or two of the larger asteroids can occasionally be seen with the unaided eye.

Perhaps massive Jupiter prevented the formation of a large planet in the space between Mars and Jupiter. Or perhaps an ancient planet (or several small planets) broke apart. The parts could have collided again and again producing thousands of tiny asteroids. Most of the asteroids move in a nearly circular orbit around the sun. A few have orbits that pass close to earth.

Sometimes a small asteroid does collide with the earth. It is then called a **meteorite.** A large meteorite is shown in Figure 20–17. As meteorites hurtle into the earth's atmosphere at high speed, the friction with the air causes them to burn with a great brilliance. Sometimes the whole sky lights up.

You may never witness the spectacular passage of a large meteorite through the air and its landing on earth. But all of us have seen **meteors.** Those streaks of light on the night sky are sometimes called "shooting" or "falling" stars. Meteors are tiny bits of matter (smaller than meteorites) that burn up completely long

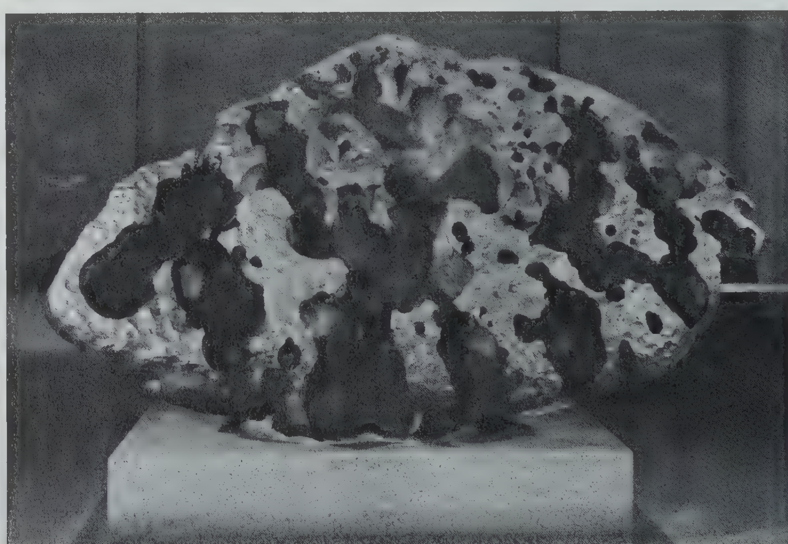


FIGURE 20–17
The Willamette meteorite, the fourth largest known meteorite in the world, weighs fifteen tons. As it plunged through the earth's atmosphere, its surface melted, and deep pits formed.

before they can reach the ground (and officially become meteorites.)

On a clear night, especially when there is no moon, and you are away from street lights, you can see several meteors an hour by patiently watching. Sometimes meteors occur in "showers" of many thousands per hour. Some meteor showers occur on schedule every year at the same time. One annual meteor shower is called the Perseid shower because the meteors all come from the direction of the constellation Perseus. This shower occurs around August 12 every year. If you could view the shower simultaneously from all parts of the earth, you would see thousands of meteors a minute. These meteors come from a huge swarm of particles that collides with the earth at the same time each year.

20–10
Comets

Comets travel in broad orbits around the sun. These sometimes spectacular objects leave a trail of debris along their paths (Figure 20–18). The earth annually passes through a few broad bands of scattered debris, and we have a meteor shower. These showers only happen when the orbit of a comet passes near the orbit of the earth.

Comets are different from planets (Figure 20–19). They form a separate family within

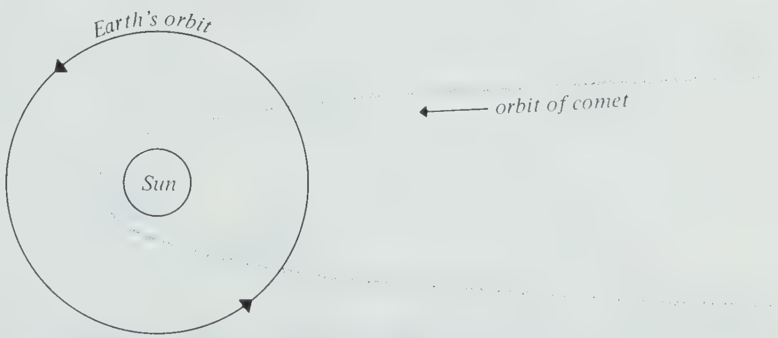


Figure 20–18
How many times a year would this comet's debris cause a meteor shower on earth?

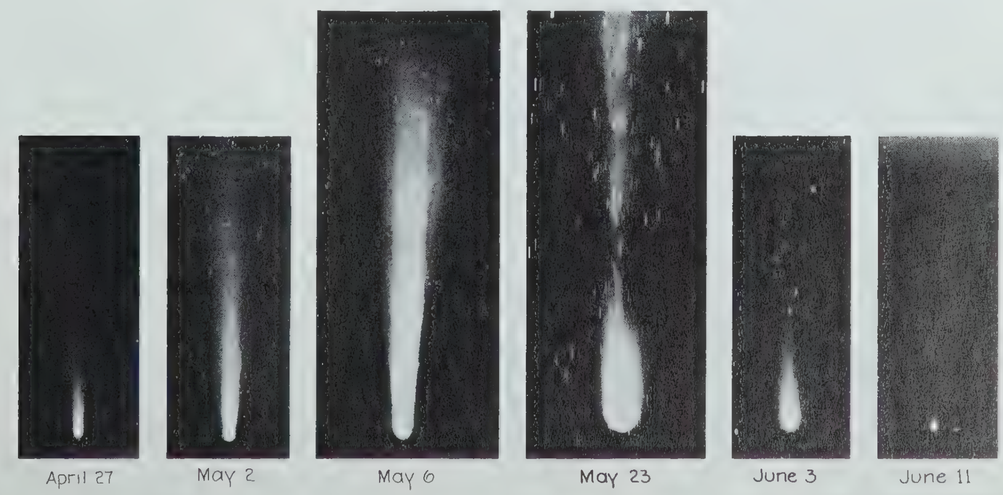


Figure 20–19
These photos of Halley's comet were taken between April 27 and June 11, 1910.

the solar system. All the planets travel around the sun in about the same plane. Comets travel on elongated orbits which carry many of them far beyond the region of the planets. Their orbits are in many different planes. Therefore, comets can appear in any part of the sky. Comets are so light that their mass has never been measured. It would probably take one billion of them to equal the mass of the earth.

Planets can be seen almost any night, but comets are rarely visible and appear suddenly. With a few exceptions one cannot predict when a bright comet will be visible. This is because most comets have periods of thousands, even millions of years. When these comets were last in our part of the solar system, there were no astronomers around to plot their orbits.

Halley's comet is due in our skies again in 1985–86. It is an exception. Because its orbit does not extend much beyond that of Neptune, it returns to our part of the solar system every 75 years.

When first discovered at an observatory or by an amateur astronomer, a comet has no glorious tail stretching millions of miles behind it. It looks merely like a faint blob of light. A comet only has a tail when it is near the sun. The heat of the sun warms the frozen material of the comet head, which "boils out" and streams away from the comet. The material in the comet's tail is propelled by the pressure of sunlight and by charged particles called the "solar wind." These particles constantly stream outward from the sun. Thus a comet tail always points away from the sun. When the comet swings around the sun on its way to the outer reaches of the solar system, the tail goes first.

A comet loses some of its material on every trip around the sun. Any one comet has a relatively short life. At the rate that Halley's comet is wasting away, people a few thousand years from now will not see it. If all comets slowly disappear, why are there any left? One theory is that there exists a huge reservoir of comets beyond the orbit of Neptune. They travel on nearly circular orbits and, therefore, never come close to the sun. Sometimes a circular orbit is changed slowly into an elliptical orbit. Then the comet becomes trapped into visits to the inner solar system where its days are numbered.

20–11 The origin of the solar system

We do not know exactly how our solar system was formed. We do have many clues. For example, comets are composed of the lighter elements in the form of dust and frozen compounds of hydrogen, carbon, oxygen, and nitrogen. Some astronomers theorize that comets are the left-overs from the original cloud of material that formed the solar system. This cloud was also composed of hydrogen, helium, and other light elements, with only a trace of heavy elements like iron.

A number of independent methods of dating earth and moon rocks and meteorites give an age for the solar system of about 4.5 billion years. Astronomers agree that the sun and the planets probably were formed at about the same time.

One theory of the origin of our solar system is based on observations of other parts of space.

Scattered throughout our galaxy are numerous globules of dust and gas (Figure 20–20). They are cold and dark. They are only visible because they block the light from more remote stars. These globules seem to be condensing and contracting, as they must by the law of gravitation. After many thousands of years, the pressure and temperature at the center of the globules will become great enough to produce nuclear energy. A new star will be born. The contracting cloud will spin faster and faster. As the central part condenses to form the star, the outer parts will condense and form planets and their moons.

This theory was originally proposed by the French scientist Laplace. It was discarded because it predicted that the sun would have to spin faster and faster. The sun is not spinning rapidly today. It takes 25 days to turn once on its axis. As can happen in science, one factor was not considered. Calculations show that the magnetic field of the cloud would act as a brake on the spinning central portion. The spin of the central star would be transferred to its planets. The old discarded theory has been revived. It is still a theory, though. The details are difficult to work out, but it seems reasonable to most astronomers.

It is both a sobering and exciting thought to realize that virtually all the knowledge we have about the solar system—and about the entire universe—has been learned by mankind in only the past few hundred years.

Thought and Discussion

1. We live on one of the smaller planets that revolve around the sun. Would it be better if we lived on one of the larger ones?
2. We live at the bottom of a deep "ocean of air." How does this make it harder for us to learn about the universe?
3. Are the orbits of astronauts as they circle the earth or the moon like the orbits of the moon and planets. Do they obey the same laws of celestial mechanics?
4. Suppose you were an astronaut whose mission was to land on Venus. How would your task differ from that of the astronauts who

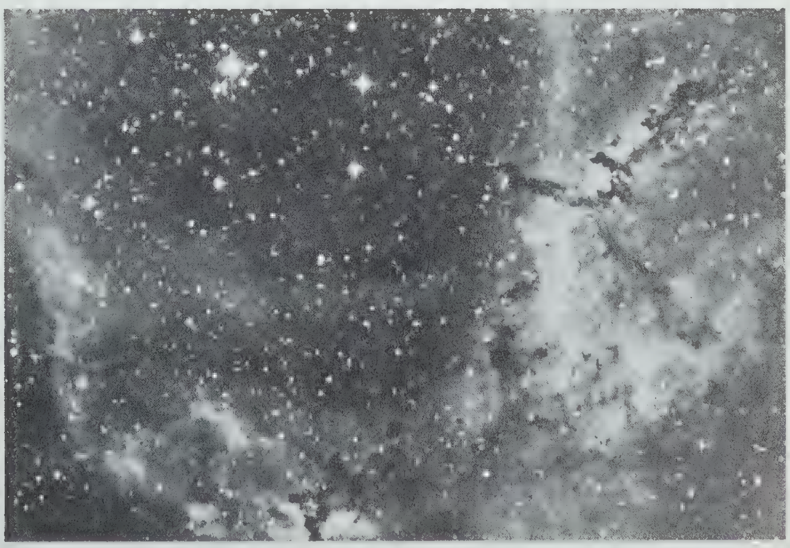


Figure 20–20
An enlarged section of the nebula in Monoceros.

landed on the moon?

5. Why is Pluto grouped with the terrestrial planets rather than the major planets?

Unsolved Problems

Our sun is only one of more than 100 billion stars in our own galaxy. The formation of planets may be a natural thing that happens to many stars when they are being formed. Therefore, there can be millions of other solar systems in space. To many astronomers it seems unlikely that our earth should be the only planet in the universe to have life.

There may well be many civilizations in space, some behind us, some well ahead of us in development. Perhaps many civilizations have prospered in our galaxy even before our solar system was born. When we consider what exciting things have happened here on earth in just the past 100 years, what might civilizations be like who had a million years or more head start? What things such civilizations must know that we have yet to learn!

Chapter Review

Summary

The earth is a member of the solar system, an orderly arrangement of bodies of greatly varying size. All members of the solar system move around the sun under its gravitational control. The members of the solar system include the terrestrial planets like Mars and Venus, the giant planets like Jupiter and Saturn, comets, asteroids, and meteoroids. All of these bodies move on elliptical orbits. They obey "laws" that were discovered by Kepler and mathematically explained by Newton.

For many centuries before Kepler and Newton, it was believed that the earth was the stationary center of the universe. Man himself was thought to be a special product of creation. It now seems likely that there are many other solar systems in space and probably other civilizations too.

The solar system is isolated in space. The nearest neighbor star is more than four light years away. That is much too far away for any telescope to see whether it has planets. Modern theories strongly suggest that planets may be the rule rather than the exception among stars like the sun.

Man can now explore the solar system in a manner unthought of not many years ago. With men in satellites and instrument-carrying space probes we begin a new era in the exploration of the solar system.

Questions and Problems

A

1. What are the main differences between the terrestrial and the major planets?
2. Why are there thousands of small asteroids between the orbits of Mars and Jupiter instead of one large planet?
3. How would a massive planet beyond the orbit of Neptune make its presence known to astronomers even if it could not be seen?

B

1. Discuss the chances that there may be millions of other solar systems in our galaxy.
2. How would the distance of a planet from its "sun" affect its ability to sustain life?
3. If the earth were ten times as massive as it is, how would life on earth be different?

C

1. Suppose an astronomer discovered a planet that took eight years to go around the sun. What would be its distance from the sun?
2. The farther from the sun a planet is, the more slowly it moves. Its speed *decreases* as the square root of its distance *increases*. Compare the speed of the earth to the speed of Jupiter. How many times faster does the earth move than does Uranus?
3. Large, long-lasting sunspots can be seen rotating with the sun. Such spots make one complete turn about the sun in 27 days. Yet, the sun rotates once in just 25 days. Try to explain this difference.
4. A comet and a meteoroid travel at the same speed when in the neighborhood of the earth. Why can a comet be seen for many nights while a meteor appears as just a streak in the sky, lasting only a few seconds?

Suggested Readings

Books

Hynek, J. Allen, and Apfel, Necia, *Astronomy One*. W. A. Benjamin Company, Menlo Park, California, 1972.

Koestler, Arthur, *Watershed: A Biography of Johannes Kepler*. Doubleday & Company, Inc., Garden City, N.Y., 1960. (Paperback)

Moore, Patrick, *The Atlas of the Universe*. Rand McNally & Company, New York, 1970.

Sagan, Carl and the editors of *Life*, *The Planets*. Time, Inc., New York, 1966.

Periodicals

Federer, Charles A., ed., *Sky and Telescope*. Sky Publishing Corporation, Cambridge, Massachusetts.

21. Stars as Other Suns

The stars are so far away that even the world's greatest telescopes can show them only as points of light. The sun is the only star with a surface we can see and telescopes can magnify. The others are too far away to be magnified. Large telescopes, however, gather much more light than the eye alone can. The larger the telescope, the more stars that can be seen and photographed.

You can choose a small portion of sky where no stars are clearly visible to the eye alone. With binoculars and then with telescopes of increasing power, an amazing sight appears. More and more stars pop into view as higher power telescopes are used. Finally, a long exposure photograph can be taken using a powerful telescope. It reveals thousands of stars where your eye could not see even one.

The sun is a star and the stars are "suns." They look so different only because the sun is much closer to us. If you could move the sun out to the distance of the "nearby" stars, you wouldn't be able to tell it apart from the others. It, too, would remain only a point of light.

Since the stars are so far away, it would seem almost impossible to learn anything about them. That is what a famous 19th century French philosopher thought. "There are some things," he said, "of which the human race must forever remain in ignorance, for example the chemical constitution of the heavenly bodies." He was wrong, of course, but only because methods of probing the nature of stars had not yet been developed.

Today we know not only what the stars are made of, but how large and massive they are,

how bright and how hot. And we know how they are moving through space. We know this not by going there and finding out, but by studying the feeble light they send to us.

The Direction and Quantity of Starlight

21–1
Measuring starlight

To find out what stars are like, we must use the information they send us. This is found in starlight. There are three things about starlight that can be measured. The *direction* in space starlight comes from is the first thing. The *quantity* of light and the *quality* or kind of radiation can also be measured.

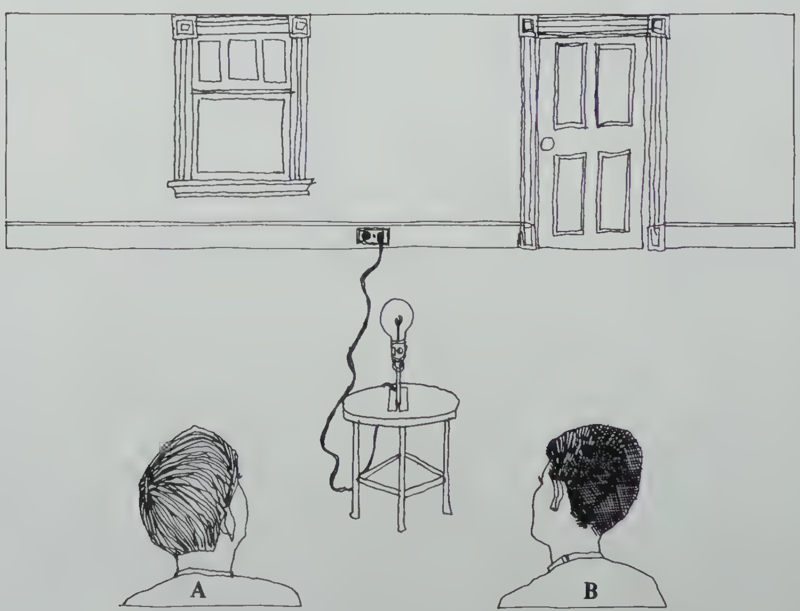
Precise measurement of star positions in the sky is actually the same as determining the direction starlight comes from. Such measurements can also tell us the star's distance. They indicate how it moves in space, and in some cases tell us how massive it is.

21–2
The distance to the stars

The distance to the moon is measured by bouncing a radar beam off it. No radar beam is powerful enough to reach even the nearest stars and return a measurable echo. That would be far more difficult than whispering across the Grand Canyon and trying to hear the echo. Astronomers use the principle of parallax to measure the distance of the relatively close stars. The following ACTION demonstrates this principle.

ACTION *Use a small electric lamp or attach some bright, shiny object like a marble or a coin*

FIGURE 21–1



to a stick and prop it up on a desk. Place yourself at position A in Figure 21–1. Sight the lamp with only one eye open. Note carefully the position of the light bulb on the opposite wall. Now move to position B (toward the other side of the room). Note where the light bulb appears against the wall.

Repeat this exercise with the lamp at different distances from you. When do you get the greatest shift in apparent position of the lamp against the wall?

When stars are photographed from opposite ends of the earth's orbit, they appear to shift their positions against the background of more distant stars. (See Figure 21–2.) The very distant stars are comparable to the wall in the ACTION. By measuring the amount of the shift, and knowing the distance across the earth's orbit (the distance from A to B by comparison), the actual distance of the stars can be determined. This method works only for nearby stars. The apparent shift (called the **parallax shift**) becomes too small to measure in the case of the distant stars. Other methods of obtaining distance must then be used.

The greatest care must be taken in measuring the photographs. Even for nearby stars, the parallax shift is tiny. The nearest star shows a total shift in position no greater than the diameter of a dime held a kilometer away. This is the star Proxima Centauri. Its distance turns out to be 40 trillion kilometers (4×10^{13}), or more than 100 million times farther away than the moon.

Astronomical distances are so great that it is convenient to use a much larger unit of distance than the kilometer. Such a unit is the **light year.** That is the distance light travels in a year (9.1×10^{12} kilometers). The distance to Proxima Centauri in this larger unit is 4.3 light years.

ACTION *If a rocket could be made to travel about ten times faster than present rockets do (say 300,000 kilometers per hour), how long would it take to get to Proxima Centauri? Light travels 300,000 kilometers per second, and there are $60 \times 60 = 3{,}600$ seconds in an hour. Could the journey be made in one lifetime?*

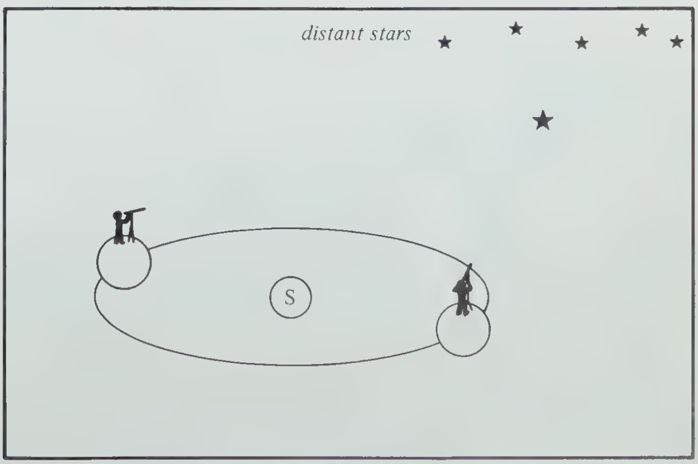


FIGURE 21–2
The distance of a nearby star can be found by measuring the amount of parallax shift against the background of more distant stars.

The light year ties together time and space. If Proxima Centauri is 4.3 light years away, light takes 4.3 years to travel from Proxima Centauri to us. Thus, if this star should explode today, we wouldn't see the explosion until more than four years had elapsed!

Proxima Centauri is visible only from the Southern Hemisphere. The nearest star visible from the United States is the bright Dog Star, Sirius, which is about 8 light years away.

21–3
The stars move in space.

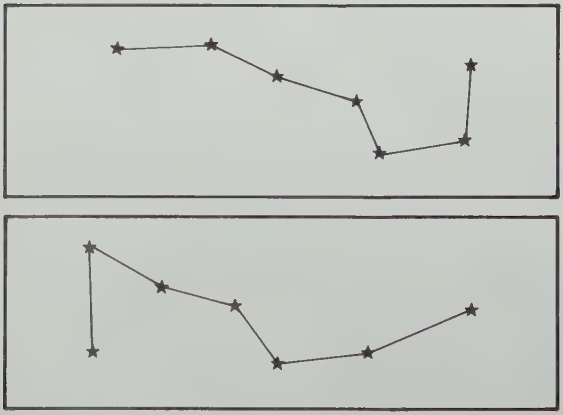
The parallax shift of a star on the sky is not caused by a motion of the star itself. It results from the motion of the earth about the sun. Stars do have motions of their own, however. These can be detected by comparing photographs taken many years apart. This motion was discovered even before the days of photography. The great English astronomer, Halley, (for whom Halley's Comet was named) was the first to show that stars really do move on the sky.

Halley compared his measurements of the positions of the stars Arcturus and Sirius with the positions listed by Ptolemy in 150 A.D. He found that these stars had appreciably changed their positions on the sky during that long interval. To a greater or lesser degree all stars show this sky motion, or **proper motion** as it is called in astronomy. Thus, the familiar constellations of stars are slowly changing their shape. The Big Dipper will not always look like a dipper (Figure 21–3).

A stars' motion directly toward or away from us is called its **radial velocity** and can be measured by the Doppler effect. To get the star's true speed as it moves across the sky, we must know the star's distance. A star, like an airplane, may appear to move slowly because it is very far away or because it really is moving slowly.

Our star the sun is also moving through space. All motion is relative. Measured with respect to the sun's neighbors, the sun is speeding at 19 kilometers per second in the general direction of the constellation Hercules. With respect to the center of the Milky Way, the sun is speeding at about 250 kilometers per second in a roughly circular orbit. As the sun moves, it carries the earth and other planets along with it on its journey. If we could view the earth from far outside the solar system, its orbit around the Milky Way would be something like a stretched-out spring. Viewed from within the solar system, the orbit is an ellipse, in accordance with Kepler's first law.

FIGURE 21–3
In time the motions of stars will change the shapes of familiar constellations. The bottom frame shows the Big Dipper's shape 100,000 years from now.



21–4
The masses of the stars

One might think offhand that it would be impossible to measure the mass of a star. But this can also be found by measuring small changes in the direction of starlight. Careful observation of the star Sirius showed that its position on the sky changed in a wiggly fashion. If there were nothing to disturb it, Sirius would move in a straight line. But it is disturbed by the gravitational pull of a tiny companion star. Sirius, like many other stars in the sky, is a double star. They both move around their common center of mass, as the moon and the earth do.

The pull of gravity depends on the mass of the object. If the mass of Sirius's companion were greater, Sirius would wiggle more. So from the size of the wiggle, the mass of the companion (and of Sirius, too) can be measured. The idea applies to all double stars, and there are thousands of them. Their masses can be found from their gravitational effects on each other. Similarly, the mass of the sun and moon are calculated by the way they swing around with the earth.

By such methods astronomers have found that the masses of stars range from less than a tenth of the sun's mass to over fifty times more massive. The mass of a star is an important quantity. It determines almost entirely how long a star will live, as you will see in a minute.

21–5
The brightness of stars

Using a photographer's light meter, we can measure the brightness of a streetlight. As we walk toward it, the exposure meter will give a higher and higher reading. If we walked halfway toward the light, we'd find that the exposure meter read *four* (not two) times as high as at the original distance. The reason is that the intensity of a light varies inversely as the square of the distance. (Review Section 6–1 if you have forgotten why.) Knowing how the brightness of a light varies with distance and our distance from the light, we can then calculate how bright the light is.

The situation with stars and street lights is similar. The amount of radiation we receive from a star depends on two things: how much it actually sends out (how bright it really is) and how far away it is. We call the true brightness of a star its **luminosity.** Luminosity is the total amount of energy radiated into space in all directions every second by the star. If we know the distance to a star, we can calculate its luminosity. First, we measure the apparent brightness of a star, called its **apparent magnitude.** Then, knowing the stars' distance, we calculate the true brightness, or **absolute magnitude.**

The system of magnitudes the astronomer uses had its origin at the time of the ancient Greeks. The Greek astronomer Hipparchus called the brightest stars on the sky "stars of the first magnitude." Stars that seemed about a step fainter he called "stars of the second magnitude," and so on. The faintest stars that you can see with your unaided eye on a dark night away from city lights are stars of the sixth magnitude. Through a telescope you can see and photograph stars that are much fainter (higher apparent magnitudes).

Apparent magnitudes for certain celestial ob-

jects are listed in Figure 21–4. The minus magnitudes refer to objects that are brighter than first magnitude.

ACTION *The apparent magnitudes of bright stars can be estimated just by using one's unaided eye. Start with Polaris, the North Star. It can easily be located in the sky by following the line of the two pointer stars in the bowl of the Big Dipper. (See Figure 21–5.) The Pole Star is at the end of the Little Dipper's handle. It is a star of the second magnitude. Trace the rest of the Little Dipper. Check how bright each one seems to you. It so happens that the stars of the Little Dipper form a magnitude scale in themselves. The next brightest star to Polaris is of the third magnitude; the next, the fourth, and so on.*

Pick some other stars in the sky that are fainter than Polaris. Judge their magnitude using the stars of the Little Dipper for comparison.

Stars vary tremendously in true brightness. Some stars are only about 1/10,000th as bright as the sun. Others are giants in luminosity, shining 10,000 times more brightly than the sun does.

An interesting fact was discovered when the masses of the stars were compared with their true luminosities. It turned out that the more massive stars had much greater luminosity or energy output. The luminosity of a star varies roughly as the *cube* of the mass. Therefore, if the sun were twice as massive as it is, it would be about eight times brighter than it is. It would also use up its fuel eight times faster.

A star's fuel is the element hydrogen, which is "burned" in the "nuclear furnace" deep inside a star to produce the element helium. In this process, starlight is created. By now, if our sun had double its mass, it would have completely burned out. So you can see the impor-

FIGURE 21–4
Magnitudes of Some Celestial Objects

OBJECT	MAGNITUDE	TIMES BRIGHTER OR FAINTER THAN POLARIS
SUN	−26.5	250,000,000,000
FULL MOON	−12.5	1,000,000
VENUS (AT BRIGHTEST)	−4	250
JUPITER	−2	40
MARS (AT BRIGHTEST)	−2	40
SIRIUS	−1.5	25
ALDEBARAN	1	3
ALTAIR	1	3
POLARIS	2	
		↑ BRIGHTER / FAINTER ↓
NAKED-EYE LIMIT	6	40
BINOCULAR LIMIT	10	1,800
10 INCH TELESCOPE LIMIT	14	60,000
200-INCH TELESCOPE LIMIT (PHOTOGRAPHIC)	23.5	400,000,000

tance of the **mass-luminosity law** for stars. The more mass (fuel) a star has to start with, the faster it uses it up, and the shorter is the star's life. The amount of matter a star is born with pretty much determines its life cycle. This is the reverse of what happens with fuel on earth. A pile of logs burns much longer than a pile of twigs.

21–6
Some stars' brightness varies.

Most stars keep the same brightness from night to night. The stars in the Big Dipper for example look the same night after night and year after year. However, certain stars go through a cycle of brightening and dimming. The bright star Algol, "the ghoul star" in the constellation Perseus, is a good example. (Find Algol on the star chart in Appendix F and then locate it on the sky the next clear night.)

In 1782 an Englishman named Goodricke discovered that Algol appeared fainter than usual for several hours at a time. (He incidentally was a deaf mute whose hobby was astronomy.) This dimming occurred precisely on schedule every two days, twenty hours, and forty-eight minutes. His explanation was that Algol was really two stars, one going around the other. He turned out to be correct. When one star was in front of the other as viewed from earth, it blocked or eclipsed the light of the other star. We know some 3,000 stars like Algol, called **eclipsing binaries.** The way the light of such pairs of stars changes is shown in Figure 21–6.

Eclipsing binaries help the astronomer learn about the sizes of stars. This is done by noting

FIGURE 21–5
(top) Use the "pointer stars" in the Big Dipper to locate Polaris.

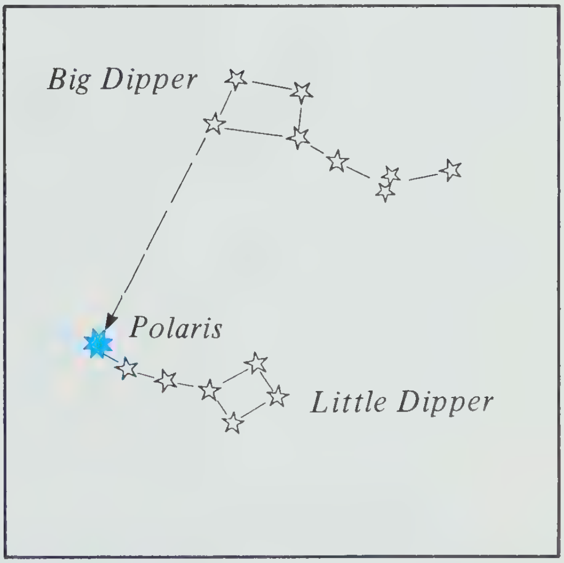
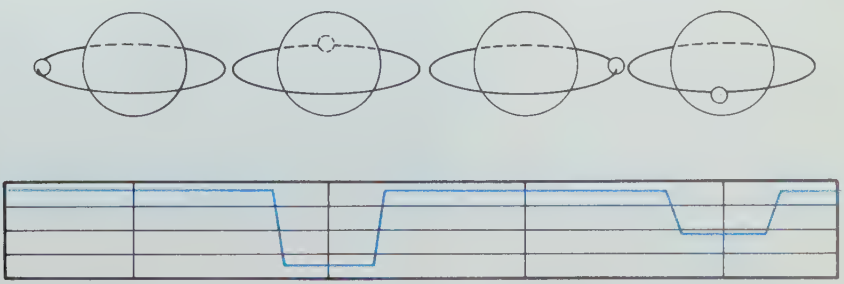


FIGURE 21–6
Each time one star eclipses the other, the total light of the system is cut down. At what point is the dimming greatest?



how long an eclipse lasts. If the period of the binary is 50 hours and the dimming is one hour long, then the diameter of the bright star is 1/50 the circumference of the orbit. Once the astronomer determines the radius of the star's orbit, he can calculate the star's diameter.

There is a wide range of sizes among stars. Some are so huge that the sun and the earth's orbit could fit inside one of them. Other stars are smaller than the sun. Some are not much larger than the earth (the white dwarfs). And some are calculated to be even much smaller than the earth (the neutron stars).

Eclipsing binary stars have constant energy outputs, but there are some stars that don't. These stars are something like balloons that expand and contract without either collapsing or bursting. As they pulsate, such stars get brighter and dimmer even though their average brightness stays the same.

One important kind of pulsating star is the Cepheid variable (SEE-fee-id). Astronomers identify these stars by the way their light varies. They are named after one of the stars in the constellation Cepheus. The time from bright to dim to bright again is called the period of the star. The important feature of Cepheid variables is that the period goes hand-in-hand with the luminosity. The greater the luminosity of a Cepheid star, the longer its period. All the astronomer has to do is to watch the star fade and brighten and note how long it takes. This tells him immediately, without further calculation, the absolute magnitude of that particular star.

Recall we said earlier that knowing the apparent magnitude and distance of a star, astronomers could calculate its absolute magnitude. In the case of the Cepheids, the calculations are reversed. Knowing both magnitudes, one can calculate the star's distance. The parallax method of getting star distances works only for nearby stars. The Cepheid method works out to very great distances, even to distant galaxies. Whenever a Cepheid variable can be found, so can its distance.

The distance to the Andromeda galaxy was first determined by the astronomer Hubble

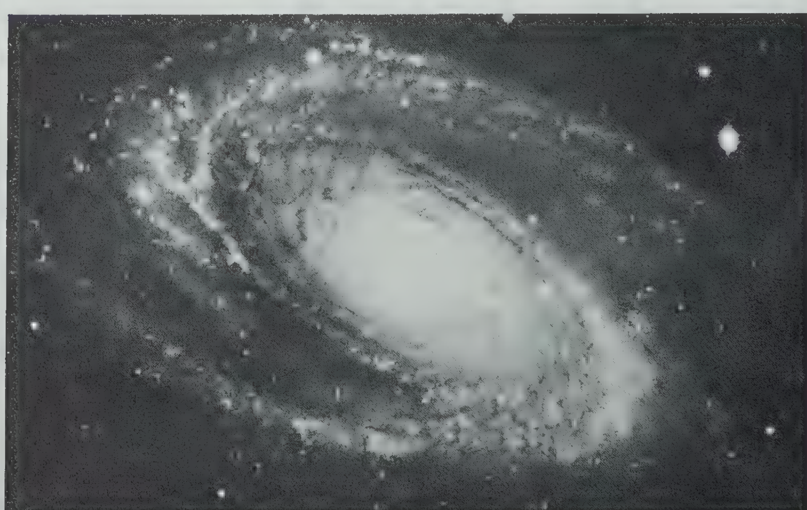


Figure 21–7
A nearby giant spiral galaxy in Ursa Major.

from his discovery of many Cepheid variables in that distant mass of stars. The power of the Cepheid method for getting distances is apparent when we realize that the Andromeda galaxy is so far away that its light takes over two million years to get here.

Thought and Discussion

1. All stars except the sun appear only as bright but unmagnified points of light even in the greatest telescopes. How then is it possible to obtain information about these stars (their distances, sizes, luminosity)?
2. Give some examples of the parallax principle from everyday life (e.g., looking at a close object first with one eye, then with the other).
3. Nearly all of the stars that are closest to the sun are invisible to the unaided eye. How is this possible?

Stellar Spectra

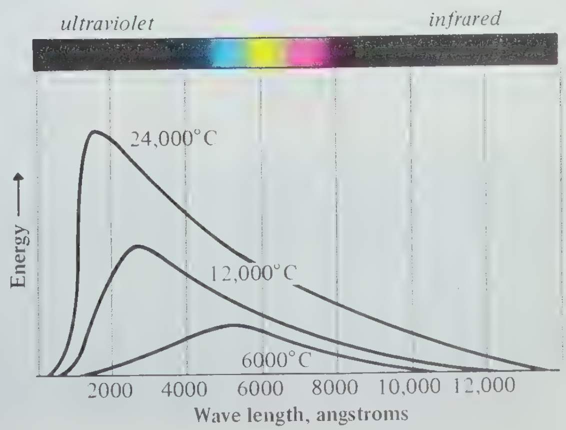
21–7 Colors and stellar temperatures

The radiation from any star can be arranged in order of wavelengths (colors). The lower energy, longer wavelengths are red. The higher energy, shorter wavelengths are blue and violet. The amount of radiation in each particular wavelength along the spectrum can vary greatly from star to star.

Radiation can tell us a great deal about the star itself. A star's temperature can be read in its starlight. A piece of metal being heated glows first with a dull red color. As it gets hotter and hotter, it becomes orange, then yellow, and finally bluish white (if it doesn't melt first). Similarly, the spectrum of a hot star is much richer in blue light than it is in red light. The opposite is true of a cool star. This is easy to see from energy curves like the three shown in Figure 21–8.

Notice that a hotter star emits *more radiation of every kind*, not just more blue radiation. It pours out more energy of all kinds from each square centimeter of its surface. By analyzing the energy curve of a star, the temperature of the surface of the star can be determined. Such methods have shown that the temperatures of the stars range from over 50,000°C for the hottest blue stars to less than 2,500°C for the coolest red stars. The sun, a yellow star, has a surface temperature of about 6,000°C.

FIGURE 21–8
Hotter stars emit more radiation of every wavelength. However, the greatest increase of energy occurs in the shorter wavelength region of the spectrum.



21–8
What stars are made of

The visible spectrum of a star is a continuous rainbow-like gradation of color. It goes from red, to orange, yellow, green, blue, and violet. Closer examination, however, shows that the smooth spectrum is interrupted by a series of fine dark lines. These are called **spectral lines** (Figure 21–9). The cooler gases in the atmosphere of a star absorb certain wavelengths of energy from the starlight passing through them. This leaves gaps in the energy spectrum. The gaps show up as the pattern of dark lines.

It was discovered about a century ago that the various chemical elements, when heated, give out light only in certain wavelengths. Each chemical element has its own distinctive set of spectral lines. (See Figure 21–10.) These wavelengths were found to correspond exactly with the dark lines in the spectra of stars. Here, then, was the clue to the chemical composition of the stars. Hydrogen and sodium, for example, each have their own characteristic set of spectral fingerprints. When these are found in the spectrum of a star, we know that those elements exist in the atmosphere of that star.

Astronomers have found that hydrogen is by far the most abundant element in the universe, with helium second. Most stars are made of about the same material as the sun, and in about the same general proportions. Fifty to 75 per cent is hydrogen, 20–45 per cent helium, and 5 per cent all other elements. It would

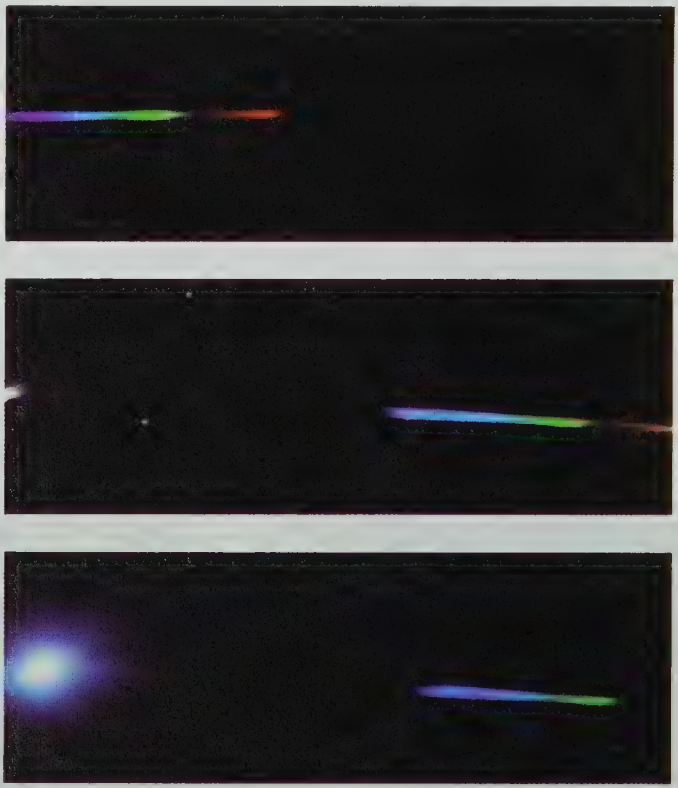


FIGURE 21–9
Typical stellar spectrograms: They are from the stars Arcturus, Vega, and Spica.

seem that the universe is chemically much the same wherever one goes.

The lines in the spectrum of a star give us another way of getting the star's temperature. We know from laboratory studies at what temperatures certain spectral lines of a given element appear most prominently. Thus, when we see those lines in the spectrum of a star, we know not only that the star contains that chemical element. We also know the temperature of the star's surface. At some temperatures chemical elements do not have any lines in the visible part of the star's spectrum. Thus the absence of spectral lines does not necessarily mean the absence of that chemical element. It may mean that the temperature is not right. The presence of spectral lines, however, always means that the chemical is present in the star.

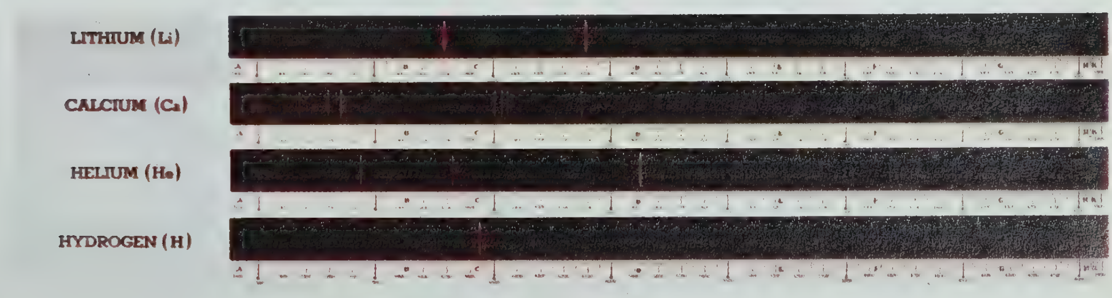
21–9
The H-R diagram of stars

There is one relation that is so important that some astronomers say modern astronomy is largely based on it. This is the relation between the temperature of a star and its total luminosity. It was discovered independently by the Dutch astronomer Hertzsprung and the American astronomer Russell. Hence it is called the Hertzsprung-Russell diagram, or more simply, just the H-R diagram.

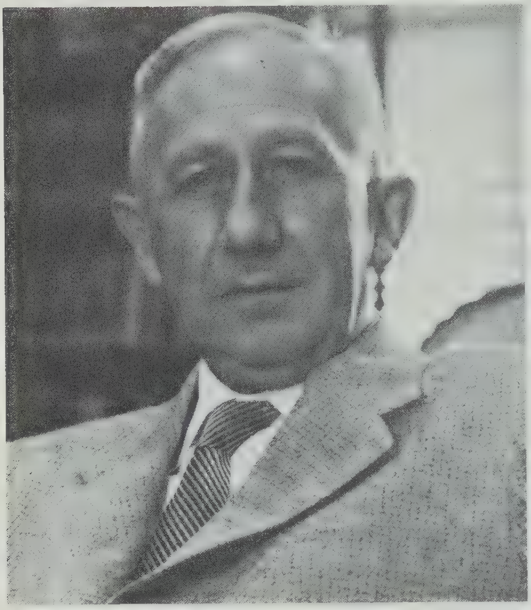
ACTION *Plot the temperature and luminosity of each of the 20 brightest stars given in Appendix F on a piece of graph paper. Plot the temperature on the horizontal scale. Have the temperatures run from highest on the left side of the graph to lowest on the right side. Plot the luminosities on the vertical scale, placing the most luminous stars farthest up on the graph. Now, using a differently-colored pencil, plot the 20 nearest stars listed in Appendix F. Finally, plot the position of the sun on this diagram.*

What pattern do the stars form? Do the positions of the brightest stars and the nearest stars differ? Is the sun more or less luminous than most of the other stars in the diagram? Is it hotter or cooler than most?

FIGURE 21–10
Spectral lines from different elements. No matter where it is in the universe, an element can be identified by its set of spectral lines.



WALTER BAADE



After receiving his doctorate in Germany, Baade (1893–1960) worked as an astronomer at the Hamburg Observatory. In 1931 he came to the United States to work at the Mount Wilson Observatory.

By 1944 the spiral arms of the Andromeda Galaxy had been optically resolved (separated) into individual stars. Baade took up the challenge of resolving the nucleus of the Andromeda Galaxy. He decided to use the 100-inch Hooker telescope at the Wilson Observatory. Because of the wartime blackout, the sky was free of artificial light. Baade was amazed to discover that if he used a film plate sensitive to red, the nucleus of the Andromeda Galaxy could be resolved into stars. He realized that the brightest stars in the arms of spiral galaxies are blue, whereas the brightest stars in the nuclei are red.

Baade's findings led him to the idea of two distinct stellar populations. Population I included the blue stars, which he considered young or in the process of being born from the dust and gas of space. Population II included the red stars, which he considered old and dying. Recent studies show that there are more than two stellar populations. But Baade's discoveries played a significant part in developing the theory of stellar evolution.

When you have completed the above ACTION you will have discovered for yourself the famous Hertzsprung-Russell diagram (Figure 21–11). When it was first discovered in 1913, the distances and luminosities of stars were not as well known as they are now. The discovery of the H-R diagram took much more work.

The H-R diagram shows that the majority of stars fall along a line running from the hot, very luminous blue stars at the top left of the diagram to the cool, far less luminous, reddish stars at the lower right. (They are sometimes called **red dwarfs.**) This line is named the **main sequence.** The great majority of stars lie along this temperature-luminosity line. The hotter the star, the more luminous, and hence also the more massive. (Recall the mass-luminosity law in Section 21–5.)

21–10
The life of stars

The H-R diagram was a powerful clue to the discovery of the life cycle of stars, one of the most exciting stories of modern science. We now know that stars are born, live, and die. The sun, for instance, we believe was born about 6 billion years ago and has about that long yet to live. It is at the "prime of life" as a star.

The energy output of stars is so tremendous that a star's fuel must sometime be used up. For instance, the sun pours out energy equal to 400,000 million, million, million constantly-shining 1,000 watt bulbs. From fossil records we know that the sun has shone with that energy for millions upon millions of years. The answer to the great question of what fuel supplied these enormous outputs of energy came late in the first half of the 20th century. The sun's fuel is its own supply of hydrogen. The hydrogen is transformed into helium by nuclear processes going on deep in the sun's interior. (Review Section 3–6.)

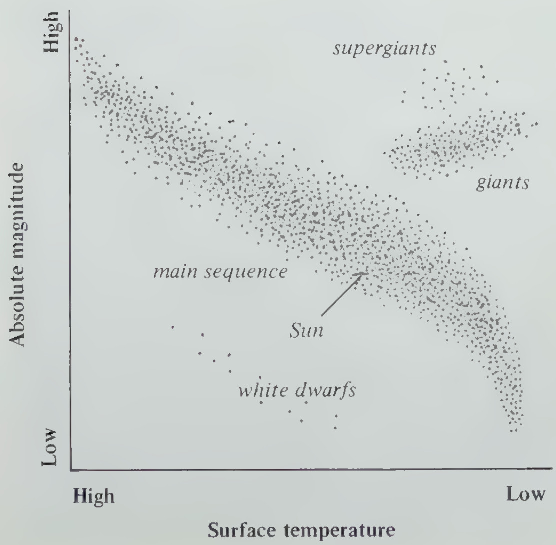
We learn from nuclear physics that when hydrogen is transformed into helium, a small amount of matter is transformed into energy. The vast output of the sun calls for the annihilation of 4.5 million tons of matter *each second!* This amount of matter is destroyed when about 600 million tons of the sun's hydrogen are transformed into about 595.5 million tons of helium.

Each second the sun weighs 4.5 million tons less than it did the second before, and is richer in helium. The sun is so massive, however, that even this seemingly great mass loss is very small in terms of the whole sun. The sun has enough fuel left to keep shining much as it has in the past for the next several billion years.

The same is not true of some other stars. We have said that a star that is 10 times more massive than the sun radiates more than 1,000 times as much energy as the sun does. Simple arithmetic shows us that if it uses its fuel 1,000 times faster than the sun does, but has only 10 times as much fuel, it can live only about 1/100th as long as the sun. Imagine a rich man who spends his money 1,000 times faster than a man who has only 1/10th as much to begin with. Who will soon be the poorer of the two?

A star starts out as a large cold dark blob of gas. It slowly contracts under its own gravitational pull. As millions of years go by, the temperature and pressure at the center continue

FIGURE 21–11
The Hertzsprung-Russell diagram. How are the absolute magnitude and the surface temperature of a star related?



to increase. Eventually they are high enough for nuclear reactions to take place. The globe of gas has become a star. For millions of years thereafter it shines as a star on the main sequence. Whether it spends its fuel like a miser or a spendthrift, the star will live most of its life on the main sequence.

Eventually its hydrogen supply near the center becomes depleted. One might think that the star would soon grow dim and fade away. Exactly the opposite happens. The star at that stage increases many times in size and shines much more brightly than before. The "ignition" of fuel farther from the center of the star causes this great change. Meanwhile, helium collects at the center of the star like ashes in a furnace. These "ashes" shrink together and finally become so hot that they are transformed into carbon, oxygen, and still heavier elements. Of course, eventually the star must die, when all its available fuel supply is gone.

It will surprise you to learn that astronomers actually know more about the insides of a star than they do about the inside of the earth. This is because the architecture of a star, which is entirely gaseous, is much simpler than the architecture of the earth.

The life history of a star is called **stellar evolution.** It begins with its formation as a dark glob of dust and gas, before it joins the main sequence. It lasts until the time it leaves the main sequence to become a giant, than a white dwarf, and finally ceases shining.

The evolution of stars that were born with many times the mass of the sun is more spectacular and explosive. As such stars grow old, temperatures and pressures inside become enormous. At a critical stage there is both a huge collapse and an explosion. The star collapses when suddenly the force of gravity of the inner mass of the star wins out over the outward-pushing forces. During this great implosion the inner parts of the star fall in on themselves. A fantastic amount of energy is then released that explodes the outer parts of the star into space.

During this short but complex process, many of the heavier chemical elements are formed. These are scattered out into space by the explosion. They become part of the dust and gas from which new stars, and probably new solar systems too, will be born. It is very likely that the iron in your blood and the calcium in your bones were once inside an ancient, massive star.

21–11
Star dust

The space between the stars of our galaxy is not empty. There is much matter spread out between them. But it is spread so thinly that the space between the stars is actually a better vacuum than we can produce on earth. Because space is so vast, there is about as much dust and gas between the stars as there is matter in all the stars put together.

FIGURE 21–12
(top left) The Great Nebula in Orion.

FIGURE 12–13
(top right) The Trifid Nebula in Sagittarius.

FIGURE 21–14
(bottom left) The gaseous nebula in Serpens.

FIGURE 21–15
(bottom right) The Horsehead Nebula in Orion.

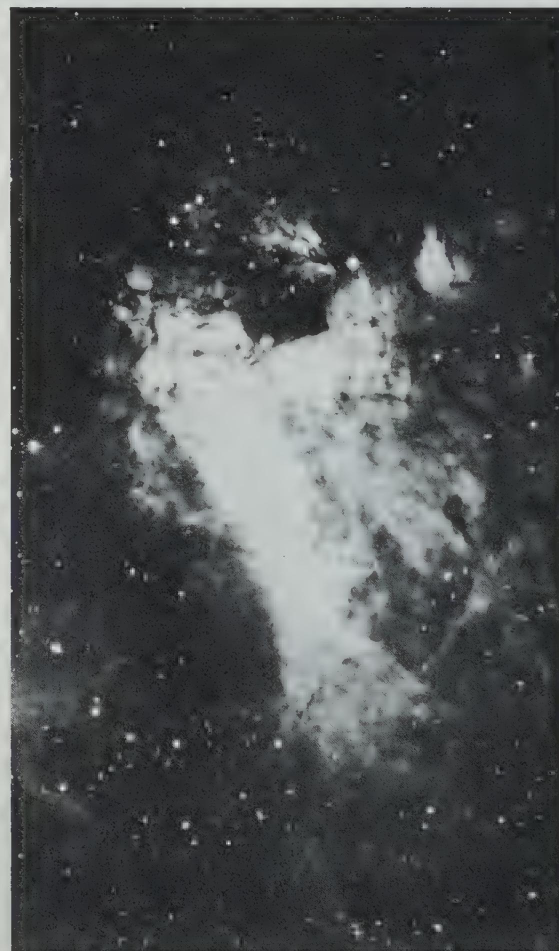



Sometimes the clouds of dust and gas become magnificent celestial displays. When such a cloud is near bright hot stars, the ultraviolet light from those stars causes the gas to glow in many colors. These otherwise dark objects are transformed into beautiful **nebulae.** The Orion Nebula is a good example (Figure 21–12). So is the Trifid Nebula (Figure 21–13) and the nebula in Serpens (Figure 21–14). Such bright nebulae, which are inside our own galaxy, should not be confused with the galaxies that also appear as nebulous spots on the sky. These other galaxies are huge systems of stars lying far out in space.

Sometimes these clouds of dust and gas, "celestial smog," block the light of stars lying behind them. Then they stand out in dark contrast to their surroundings. A fine example of

FIGURE 21–16
(left) Dark and light nebulae in Monoceros.

FIGURE 21–17
The "Omega" Nebula contains dark "globules."



this is the Horsehead Nebula in Orion (Figure 21–15). The dark lanes in the Milky Way are also an example of the blocking of light from distant stars. A great many other galaxies show dust lanes as well. Often bright and dark nebulae appear together as shown in Figure 21–16. Part of the gas cloud is illuminated by nearby stars, while the dust in other parts of the cloud is silhouetted against distant stars.

Concentrations of dust and gas sometimes appear as "globules" (Figure 21–17). Many astronomers think that these are new stars, and perhaps even solar systems, in the process of being formed. The dust and gas are not yet sufficiently contracted to have arrived at the nuclear energy stage. Recent photographs of the Orion nebula region show stars that were not visible on photographs of the same region taken years ago. Before the sun began to shine and the planets were just forming, our embryonic solar system might have appeared like the globule shown in Figure 21–17.

Thought and Discussion

1. What are the differences between galaxies and nebulae?
2. If two stars were formed at the same time, but one was more massive than the other, which one would shine the longest? Which one would be brighter?

Unsolved Problems

The later stages of stellar evolution are poorly understood. This is because of the difficulty of the computations involved, which require the use of high speed computers.

The early stages of a star's history are also imperfectly known. Much work must yet be done on the kinds, amounts, and motions of the dust and gas that lie between the stars. How this interstellar material comes together to form stars and, in our case especially, a solar system, is far from clear. Astronomers believe they have the general outlines of the process. But in actual fact, we do not yet know how our solar system formed.

Chapter Review

Summary

By observing the direction from which starlight comes, and measuring its quantity and quality, astronomers can find out the following things about stars: their distance, speed, chemical composition, mass, size, temperature, and luminosity.

When the temperature and luminosity of a star are plotted on a diagram, the majority of stars are found to lie on a broad band called the main sequence. A smaller number form another band called the giant branch. These giants are stars that have evolved off the main sequence.

A star generates its light by the conversion of hydrogen into helium and, later, into still heavier elements. While the hydrogen supply in the center of a star is plentiful, the star remains on the main sequence of the H-R

diagram. Later, the helium "ashes" in the center of the star are transformed into heavier elements. The star evolves to the giant branch, expanding greatly and becoming brighter. This unstable giant finally shrinks to the white dwarf stage. The most massive stars, however, suffer a violent explosion. They scatter their substance and newly formed elements far into space.

A star begins its life as a large, but cold and dark cloud of dust and gas. This contracts and becomes smaller, and denser. The temperature at the center finally rises so high that the dark cloud begins to shine as a star. It continues to shine until its fuel, hydrogen and later helium, is depleted.

During the condensation from a large, formless cloud to a ball of luminous gas, it is thought that many stars develop systems of planets, such as our sun has. Some astronomers believe that there may be many millions of other solar systems.

Questions and Problems

A

1. Star A is twice as massive as star B. Which one will have the longest lifetime? Which one will be hotter?
2. How many kilometers per hour does light travel?
3. Why does the direct parallax method work only with relatively nearby stars?
4. In what two ways can the temperature of a star be determined?
5. Discuss the sun's position on the H-R diagram.

B

1. Why do you think that astronomers call our sun an average star?
2. Why can't a telescope magnify a star? How can we see so many more stars through a telescope than with the eye alone?
3. Why will the constellations not look the same many thousands of years from now?
4. If a star is moving *directly* toward us, will it show any proper motion? radial velocity?
5. Why does a star have to be a member of a double star system before we can determine its mass directly?

C

1. Why is it that a photograph can show us more than we would see by just looking through the same telescope used in making the photograph?
2. Suppose that a star that is 10 light years away has a planet with an advanced civilization. If we should happen to hear a radio program from that planet, how long ago would that program have been broadcast?
3. Two Cepheid variable stars appear equally bright in the sky. One of them has a much longer period than the other. Which one is farther away?
4. A star of the 1st magnitude is exactly 100 times brighter than a 6th magnitude star. A 6th magnitude star is 100 times as bright as an 11th magnitude star. How many times brighter is a first magnitude star than an 11th magnitude star? The faintest stars that can be seen through a telescope are about the 23rd magnitude. How many times fainter

are these stars than stars of the 18th magnitude? than stars of the 13th magnitude?

Suggested Readings

Abell, G. O., *Exploration of the Universe*. Holt, Rinehart & Winston, Inc., New York, 1964.

Benjamin, David and the editors of *Life*, *The Universe*. Time, Inc., New York, 1966.

Hynek, J. Allen, and Apfel, Necia, *Astronomy One*. W. A. Benjamin Company, Menlo Park, California, 1972.

Hynek, J. Allen, and Anderson, Norman D., *Challenge of the Universe*. McGraw-Hill Book Company, New York, 1962.

Menzel, Donald H., *A Field Guide to the Stars and Planets*. Houghton Mifflin Company, Boston, 1963.

22. Galaxies and the Universe

We are all part of one vast organization and collection of things called "the universe." The universe is all the things that are: space, galaxies, stars, our solar system, the earth and all the things on it and in it—including you and me.

Have you ever wondered how it all came to be? And why this particular universe? Was it some great accident? Could there have been another universe, differently constructed, from this one? Or is there another universe made of entirely different elements somewhere else? Since there is absolutely no way we know of to test such ideas, these are not scientific questions. Science can deal only with matters that can be investigated and tested, accepted or rejected on the basis of evidence.

The study of the spectra of stars and analysis of meteorites reveals a tremendously important fact about our universe. No matter where we look, the chemical elements are the same throughout the universe. All the universe apparently "cooked in the same pot." This is a very simplifying fact. Think how difficult scientific study of the universe would be if each galaxy had a different set of chemical elements!

As far as we know, all the heavier elements were built from the simplest element of all: hydrogen. Thus the entire universe is made up of the same "universal stuff." And amazing stuff it is. In different combinations it has made stars, forests, and waterfalls. It has also made man and the things that man creates.

How about hydrogen itself? Where did it first come from? Hydrogen is very simple: a positively-charged proton and a tiny negatively-charged electron. These two bits of charged

*matter are, however, separated from each other by **relatively** as much space as there is between the sun and the earth. So it would seem that matter is mostly space.*

We Live in a Galaxy

22–1
The earth in the Milky Way

The sun, all the stars we can see on a clear night, and millions more we can see through a telescope all belong to a huge system of stars we call our **galaxy**. All told, it contains over 100 billion stars. It is shaped like a thick disc with a bulge in the middle (Figure 22–1).

On a clear, moonless night, far away from city lights, a broad milky band can be seen stretching across the sky. The ancients called it the "via lactea" or Milky Way. It completely encircles the sky, which means that we are somewhere within it.

When Galileo first directed his telescope toward the white band of the Milky Way, he was surprised to see countless thousands of faint stars. Today we know that when we view the Milky Way, we are seeing the thickest part of our galaxy from within.

When we look in the directions indicated by the solid arrows in Figure 22–1, we look along the plane of our disc-like system of stars. There are so many stars to be seen in those directions, and they are so far away, that they all blend together into a white, circular band. If we look in the directions indicated by the dotted arrows in Figure 22–1, we are looking out at right angles to the Milky Way disc. We, therefore, see relatively few stars.

The Milky Way is not equally bright in all directions. It is much thicker and brighter in the direction of the constellation Sagittarius. It is faintest in the opposite part of the sky, in the direction of the constellations Auriga and Cassiopeia. We conclude that the center of our galaxy lies in the direction of Sagittarius. Our solar system lies at a great distance from the center.

How far our sun really is from the center of the Milky Way galaxy was not answered until about 40 years ago. The distances of remote clusters of stars were painstakingly plotted, often by the use of Cepheid variables found in those clusters. It was deduced that we are some 30,000 light years away from the center, not far from the plane of the galaxy. More recently it was shown that many of the stars of the Milky Way form a pattern of arms spiralling outward from the thick center. The sun is imbedded in one of these arms. What our galaxy might look like viewed from outside is shown in Figure 22–2.

The speeds of stars that lie in different directions and distances from the sun can be measured. These measurements reveal that the entire Milky Way is rotating about its center like some giant pin-wheel. Each star in the Milky Way pursues its own orbit around the center of the galaxy. It is difficult to study the center itself because it is far away and shrouded from us by cosmic dust. We do know that stars closer to the center move faster than those farther

FIGURE 22–1
The spiral Milky Way galaxy: (left) as it might appear from outer space and (right) a cross section.

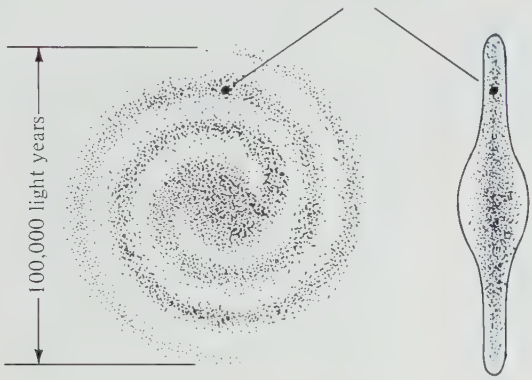


FIGURE 22–2
The Whirlpool galaxy in the constellation Canes Venatici (Hunting Dogs).

out, just as Mercury moves about the sun faster than the earth or Mars do.

The sun goes around the center of the Milky Way for the same reason the earth goes around the sun: gravity. All the matter between the sun and the center of our galaxy exerts a gravitational pull on the sun. As the stars circle the galactic center, the shape of the galaxy slowly changes. The sun travels at about 250 kilometers per second. But the sun's orbit is so large that it takes more than 200 million years to make one revolution. This might be called a solar or cosmic year.

One cosmic year ago dinosaurs were just beginning to roam the earth. Will *Homo sapiens* still be here one cosmic year from now? That probably depends more on how mankind solves the problems of life on earth than on cosmic factors.

22–2
Other galaxies

Except when the stars and dust of the Milky Way block our view, no matter where we look, or how far out, we see galaxies and more galaxies, clear to the limits of the power of our mightiest telescopes. Galaxies and clusters of galaxies are the real "building blocks" of the universe. Billions of stars make up each galaxy. But between the galaxies is empty space. This intergalactic space is virtually a vacuum. Occasional stars may wander in the awesome spaces between galaxies, like lonely travelers in wide open country between towns.

Living inside a galaxy makes it difficult to visualize it as it would appear from far outside

—a huge system of stars, dust, and gas. We are like an invalid who is confined forever to his house and can never see the outside of his house for himself. However, we can look out and see what other "cosmic houses"—other galaxies—look like.

Most galaxies are so far away that they are only visible on long time exposure photographs taken with high powered telescopes. The Andromeda galaxy in Figure 22–3 is the closest giant galaxy to us. Astronomers believe that our own galaxy would look similar to the Andromeda galaxy from a distance of two million light years. But as one house differs somewhat from the next, although they are all houses, so one galaxy differs in shape and appearance from another.

Our galaxy is nearly 100,000 light years across and several thousand light years thick in the center. Like some others, it has a "halo" of huge families of stars, globular in shape, and hence called **globular clusters.** These are all at large distances from us. A good example is the great cluster in Hercules (Figure 22–4). It is like a swarm of thousands of bees, traveling through space together. The stars in the cluster look very crowded together, but this is an effect of distance. No collisions between stars have yet been observed.

Many galaxies exist alone in space. But other galaxies, like stars, are found in clusters (Figure 22–5). The Milky Way belongs to a small cluster of about twenty galaxies. Other clusters may contain many hundreds of galaxies.

FIGURE 22–3
Andromeda is the nearest spiral galaxy.

Figure 22–4
The globular cluster in the constellation Hercules. It contains many thousands of stars that are closely packed (for stars) into a spherical shape.

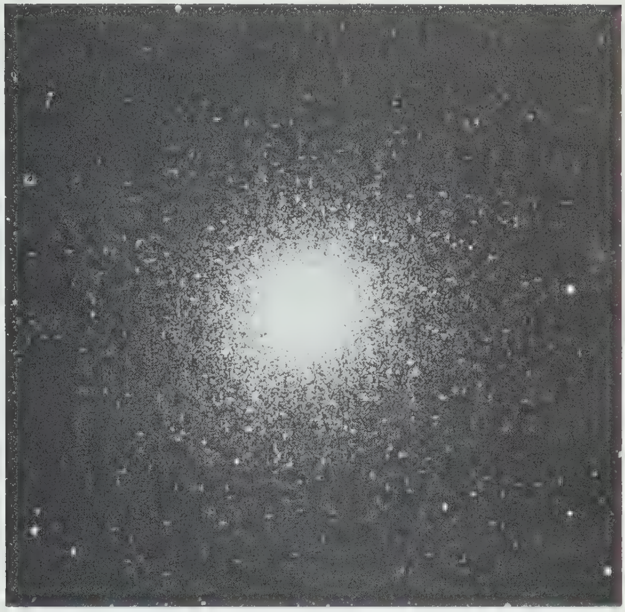
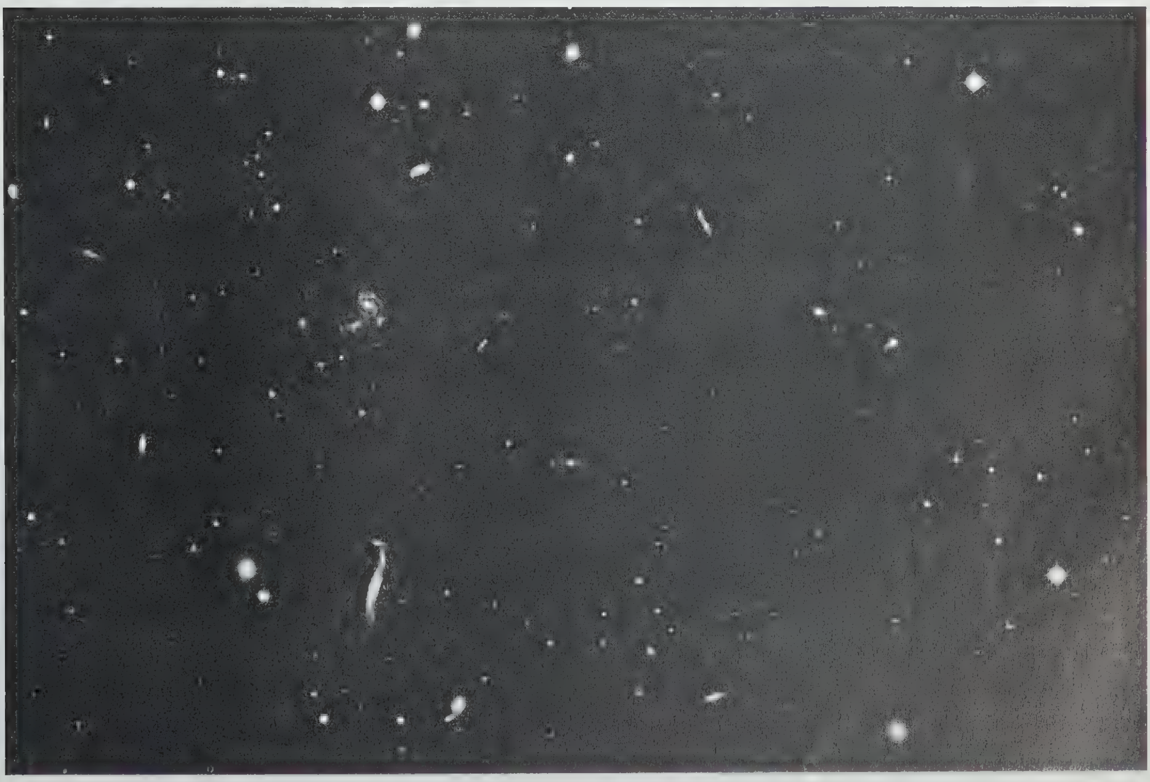


Figure 22–5
Cluster of galaxies behind the constellation Hercules. The stars in the constellation are in our own galaxy.



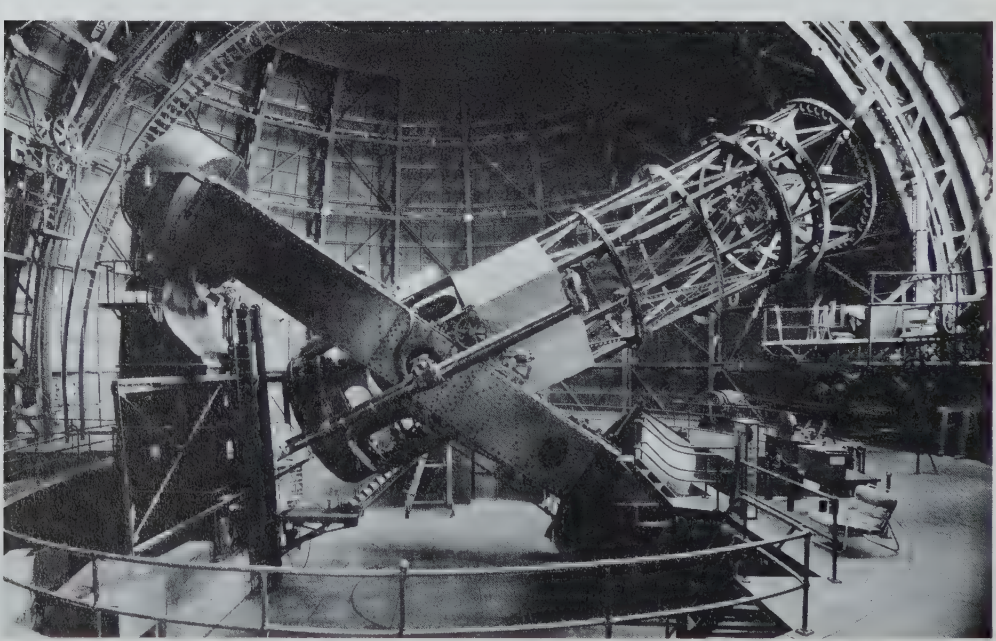
The true nature of galaxies was only learned about 50 years ago. Only by the use of the largest telescopes and modern photography did it become possible to see individual stars in even the nearby galaxies. Once again it was the Cepheid variables, which someone has called the "lighthouses of the sky," that gave us the answer.

In 1924 the astronomer Hubble, using the new 100-inch telescope on Mount Wilson, photographed several Cepheid variables in the Andromeda galaxy. By carefully noting how much time elapsed between their alternate brightening and dimming, he knew their true luminosity. Knowing that, it was easy to calculate how far away they had to be to appear so faint, even with the mighty telescope (Figure 22–6). He proved that the Andromeda galaxy was indeed a distant system of stars in a vast universe of which we are a very tiny part.

22–3 Deep Sky Watch

In this investigation you will be taking a journey in both space and time. Use the star charts in Appendix F to seek out objects farther away from our solar system. This will require that you choose your time and place carefully. The night must be very clear and there must be no moon. And most important of all, you must choose a place away from street or house lights.

FIGURE 22–6
The Hooker telescope on Mount Wilson. Much of the pioneering work in astronomy was done with this great instrument.



This can sometimes best be done by groups of observers going together to a favorable location.

PROCEDURE

First locate and identify some of the brighter stars in the sky. Refer to Appendix F-Part 3 for the distance of these stars. Realize as you gaze upward that you are looking back into time, as well as into space. If the distance of a star is 50 light years, you are looking at light that left the star 50 years ago. It left there long before you were born and has been traveling at 300,000 kilometers per second (about 7½ times around the earth in a second) all that time.

Locate the Milky Way on your star charts. Look for it in the appropriate part of the sky. It will appear as a faint band of light stretching across the sky. Look at it through binoculars or a telescope if possible. Only then will you see that the white band of light actually comes from countless stars. If you look toward Sagittarius, you are looking up to 30,000 years back into time. If toward Cygnus, then several thousand years back into history.

1. *Is the Milky Way uniformly bright along its course?*

If the Milky Way is plainly visible, you should be able to see breaks or interruptions. These dark regions in which few stars are visible are huge clouds of cosmic dust that block out the light of stars behind them. Without the dust clouds you'd see just as many stars in those parts of the Milky Way as in the bright regions.

2. *Is the globular cluster in Hercules (M 13) (Figure 22–4) high enough up in the sky for you to observe?*

This cluster is a beautiful object to observe through a telescope. When you see it, keep in mind that you are seeing it as it was 25,000 years ago, not as it really is tonight!

The Andromeda galaxy is visible only in the fall sky. If you have the opportunity, examine it with binoculars or with your eyes alone. On a very dark night it can be seen with the unaided eye as a very faint, blurry patch. As unimpressive as it may seem when looking at it without a telescope, remember that you are looking at light that has been traveling for over two million years. You are, one might say, looking at "fossil light." It is sobering yet thrilling to realize that for every fossil of an extinct species buried here on earth, the astronomer can find light that left some galaxy when that fossil was alive, many millions of years ago.

3. *Locate the Big Dipper. Follow the line suggested by the handle of the Dipper until it reaches a very bright star. That will be the star Arcturus, which is nearly 40 light years away. Continue the line and you will come to another star not quite as bright as Arcturus. That will be Spica.*
4. *Do you notice any difference in color in these two stars? Knowing that color and temperature are related, which of the two stars Arcturus and Spica is hotter?*
5. *Spica is about 250 light years away but it appears roughly as bright as Arcturus. How much brighter than Arcturus must it be to appear so bright and yet be so much farther away?*

Thought and Discussion

1. Do you think it would be much different if we lived in another galaxy?
2. If the sun moved on an orbit that was much

closer to the center of the galaxy, would we still see the Big Dipper? Saturn? the Milky Way?

3. What events were taking place on earth when the light you see tonight from Arcturus and Spica left those stars?

The Universe

22–4
The size of the universe

In these last 50 years, larger and more powerful telescopes have been built, both optical telescopes and radio telescopes. Astronomers have eagerly looked farther and farther out into space and longer and longer back in time. No matter where or how far out they look, they see more galaxies. With radio telescopes they even pick up the faint radio energies of galaxies too far away to be seen with optical telescopes. There seems to be no end to the *observable* universe.

One may ask about what lies beyond the present reach of our greatest telescopes—the *unobservable* universe. We do not know whether it goes on and on, or whether there is an end to it. One of the current theories is that the universe is curved in such a way that if one traveled in one direction he would eventually come back from the other, much as is the case on earth. The earth's surface is *finite* but *unbounded*. When we think of the universe, however, we must think of more than the two dimensions of the earth's surface.

It is very hard for us to imagine such things. Suppose a tiny microscopic creature living in the depths of the ocean (as we live in an immense ocean of space) had the ability to wonder and think about its "universe." It too might wonder whether its ocean went on forever, or whether it had an ending some place. Even if this little creature had tiny "telescopes" to see farther in the ocean than it could itself ever hope to travel, its observable universe might be limited to a few kilometers in any direction.

Undoubtedly, if the tiny creature possessed intelligence, it would devise various theories of what its universe might be like. We have various theories about our universe. But theories remain just theories unless they can be tested. So far, we do not know which theory is correct, or even if we have thought of the theory which eventually will prove to be the correct one. All we can say is that we know much more about the universe than we did just 100 years ago. Astronomers are hard at work in their observatories, and we can confidently expect that we shall know even more in the years ahead of us. That is what makes science exciting. How dull it would be if we had the answers to everything and there was no more need for exploration.

22–5
Our place in the universe

Suppose there were some cosmic navigator in search of planet earth. In our imagination we must give him the ability to travel much faster than light. Otherwise his job is hopeless. First, from the many billions of galaxies, our navigator must pick the right one—our Milky Way. That would be his first big problem. Imagine searching through billions of stars to find the

sun, only to find that you started in the wrong galaxy! (See Figure 22–7.)

He would need enormous, accurate charts of all the galaxies in the universe. Suppose he did succeed in finding our galaxy. His next problem would be to find the sun—one particular star out of more than 100,000,000,000. This would be an immense task and would require some highly complicated cosmic navigation. Even *one* billion is a large number. Think how fast seconds tick off. Yet you will not have lived for even one billion seconds until you are 31 years old. If you started out to count the stars in our galaxy alone, one by one, counting one each second, it would take more than 3,000 years of steady counting.

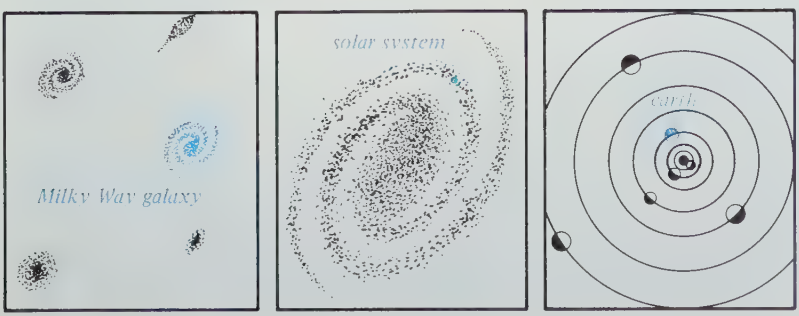
Once the navigator located the sun, his remaining task would be to find the third planet out from the sun—our earth. Even this might not be easy because the earth is small and shines only by reflected light. But it would be much easier than finding the sun in the first place.

A real cosmic navigator would have to travel much more slowly than the speed of light. For all practical purposes, the task of finding our earth starting from somewhere in far outer space would be impossible.

Perhaps we should remind ourselves that we are space navigators too. Our earth is a sort of spaceship, carrying its own climate and food supply along with it wherever it goes. While traveling around the sun at 30 kilometers per second, it travels with the sun around the center of the galaxy. The earth visits new places in space as time goes on, never coming back to the place where it is at this moment. The earth's high speed is still much slower than light. Even if we were headed directly toward the next nearest star, it would take more than 5,000 years to get there.

The faintest galaxies that we can see are many billions of light years away. Gauging the distance of these galaxies is a difficult matter. On the average, the fainter and smaller they appear, the farther away they are. This is not the best way of determining galaxy distances because galaxies do differ considerably in size. Nor do they all have spiral arms like ours, Andromeda, and the great Whirlpool galaxy.

FIGURE 22–7
How to find the earth in a universe of galaxies. First find the right galaxy. Then locate the right star, our sun. Finally, look through the solar system for the earth. The distances between planets are enormous in human terms, but insignificant in intergalactic terms.



These armless galaxies are elliptical in shape and are, appropriately, called **elliptical galaxies.** They seem to be composed only of stars. They are missing the dust and gas so prominent in our galaxy. Most of these galaxies appear only as fuzzy spots on a photograph, and only in the nearest ones can individual stars be distinguished (Figure 22–8).

In the nearer galaxies, Cepheid variables and the brightest stars can be used as distance gaugers. The period of variation of the Cepheids, as we have seen, tells us how bright they really are. Similarly, the very brightest stars in any galaxy probably have about the same luminosity. Knowing how faint they appear to us, we can tell how far away they must be.

22–6 Classifying galaxies

There are so many galaxies found on photographs taken with large telescopes that it is impossible to name or even to number them all. There are catalogues of many of the brighter and more unusual looking ones. If you look at a large number of them you will soon recognize the similarities and differences among them. It is standard scientific procedure to develop systems of classification based on observable characteristics of different objects or materials.

Procedure

In this investigation try to develop a system of arranging or classifying galaxies. Try to arrange each group of galaxies into a sequence based on its characteristics.

1. *Can you fit the spiral and elliptical galaxies into one sequence?*
2. *Do the spirals and the ellipticals by themselves form a meaningful sequence?*
3. *On what characteristics did you base your system of classification?*
4. *Does the sequence of galaxies you constructed suggest that one type of galaxy*

Figure 22–8
One of the great accomplishments of 20th century astronomy was resolving the companion galaxy to Andromeda into individual stars.

might have evolved from another? If so, which types would you consider the youngest and the oldest?

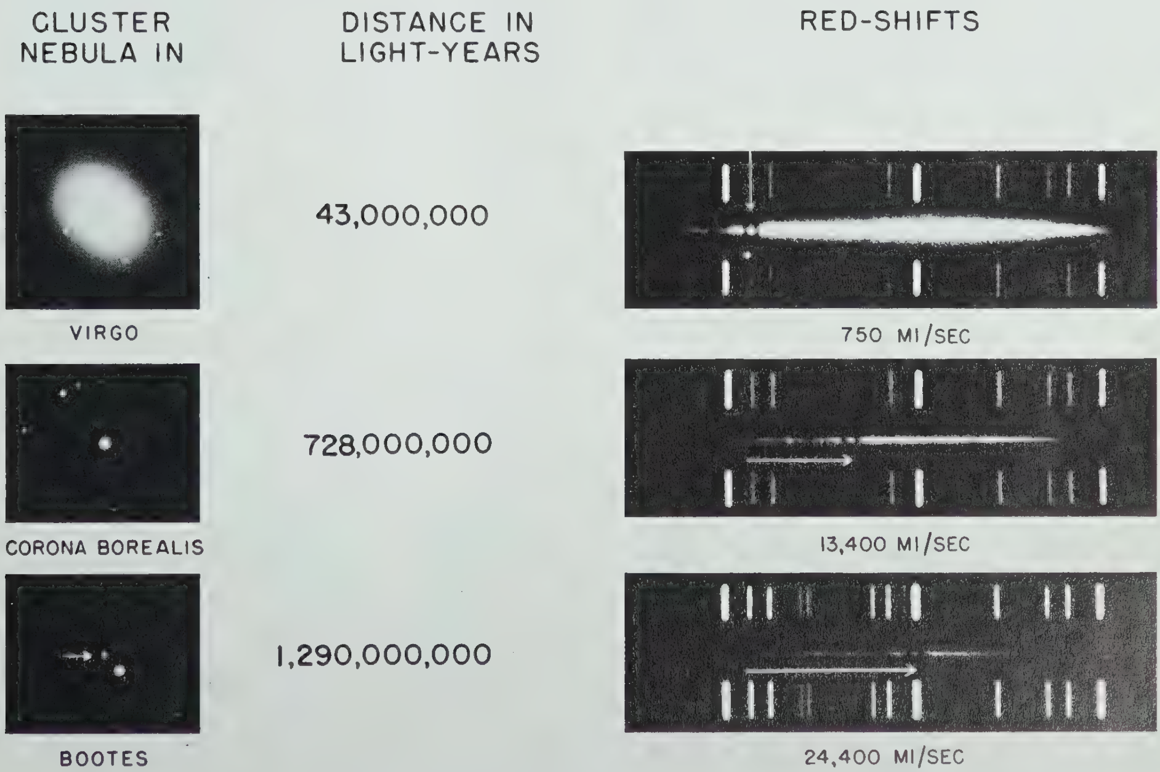
22–7 The red shift

As soon as the nature of galaxies became known, astronomers became curious about how they were moving. The earth goes around the sun and the sun around our galaxy. But is our galaxy in turn going around something else? Or is it just "suspended" in space?

Here was a job for the Doppler effect. You will recall that when a source of light is coming toward you, the spectral lines are displaced toward the blue, shorter wavelength end of the spectrum. If the light is going away from you, the spectral lines appear to be shifted toward the longer wavelength, red portion of the spectrum. They are "red shifted."

When the spectra of galaxies were obtained, an amazing thing was found. The more distant a galaxy was, the greater was its red shift (Figure 22–9). According to the Doppler effect (and there doesn't seem to be any other good

FIGURE 22–9
The relation between red shift and distance for three nebulae. The red shift, shown by the arrow; is measured by the displacement of calcium lines. Which galaxy is most distant?



explanation for it at present), everything is rushing away from us. And the farther away a galaxy is, the faster it is rushing away.

This discovery gives us a fine way to obtain the distance of a galaxy. Merely measure its red-shift, and you know how far away the galaxy is. The red shift is the difference between the observed wavelength of the spectral line in that galaxy and its value measured in the laboratory here on earth. The galaxies are separated from each other by about 20 diameters, as a very rough average. Imagine a roomful of sausage-shaped balloons suspended so that one is separated from another by about 20 times the length of the "sausage."

ACTION *Figure 22–10 is a list of galaxies arranged at random. The first column gives the galaxy designation as would be found in a professional catalogue. The second column gives the measured red-shift as a percentage. And the third column gives the speed of recession needed to produce the observed red shift. The last column gives the distance to the galaxy, obtained by other means.*

Construct a graph in which you plot the distance of a galaxy (on the horizontal axis) against the speed of recession (on the vertical axis). Find the distances to NGC 7619 and Galaxy X. You will be doing what the professional astronomer does when he measures the red shift of a galaxy and then wishes to find its distance.

What does the accuracy of your distance determination depend on? If the distances of some galaxies had not been determined independently, could you use the red shift to determine distances? Does the velocity-distance relation suggest that we are at the center of the universe? Does your graph show a straight or a curved line?

The astronomer Hubble first clearly established the relation between the red shift (expansion of the universe) and distance. Since his time, with the great 200-inch telescope, astronomers have been able to see much farther into space. The Hubble relation has been fully verified. The most distant galaxies observed do seem to be rushing away from us at the greatest speed.

FIGURE 22–10

GALAXY	RED SHIFT	VELOCITY KM/SEC.	DISTANCE LIGHT YEARS
BOOTES CLUSTER	0.13	39,000	2,600,000,000
VIRGO CLUSTER	0.004	1,200	80,000,000
HYDRA CLUSTER	0.20	60,000	4,000,000,000
URSA MAJOR	0.05	15,000	1,000,000,000
CORONA BOREALIS CL	0.07	21,000	1,400,000,000
NGC 7619	0.012	3,600	?
GALAXY X	0.30	90,000	?

Thought and Discussion

1. Think of the earth as a spaceship. How does it get its supplies? How does it manage to carry enough air for its passengers to breathe? How does it get rid of waste materials?
2. What are the most powerful methods of gauging the distances to galaxies?
3. Can you think of another possible reason for the red shift other than the actual motion of galaxies away from us?
4. What would it mean if some distant galaxies were found to have a blue shift instead of a red shift?

The Expanding Universe

22–8
Measurements are relative.

The Hubble relation is a great boon to astronomers because getting the distance to remote galaxies would otherwise be very difficult. But of far greater significance, the Hubble relation indicates that our entire universe is expanding.

You might think that our galaxy is standing still, and every other one moving. It hardly seems likely, though, that out of billions of galaxies ours should have been singled out to be the only one standing still at the center of the universe. Such an exalted position would be like the ancient illusion that the sun and stars circled a stationary earth.

No matter what galaxy we lived in, it too would appear to be the center of things. Imagine a very large theater, so large that no matter how far you look, you see nothing but seats and no walls. Suppose now that the entire theater were to begin expanding, so that the seats were continuously getting farther from each other. In this example we keep the size of the seats (galaxies) the same. Only the space between them will grow greater (Figure 22–11).

Can you see that *no matter where you sit*, every other seat will appear to be going away

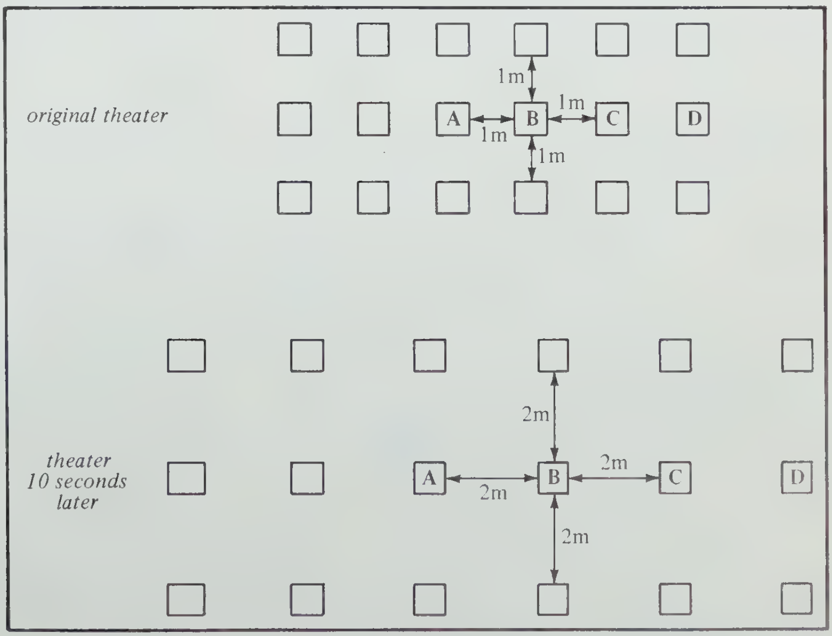


FIGURE 22–11
Imagine that A, B, C, and D are seats in an expanding theater. Is there a central seat?

from you? Figure 22–11 will help you visualize this. Consider four seats: A, B, C, and D. First, imagine yourself sitting in seat B. In the second diagram, note how the distances of A, C, and D have changed with respect to seat B. Seat C is now twice as far from you than it was originally, and D is twice as far from C as it was originally. That means that it is now *four* times farther from you than at first.

Now imagine sitting in seat A, and then in C and D. You will discover that no matter where you sit, all the other seats would seem to be going away from you. The farthest ones are going away from you fastest of all. But it would not mean that you were in the center of the room. In the same way, no matter what galaxy you live in, all others would seem to be going away from you. There is no center to the universe!

22–9 Relativity

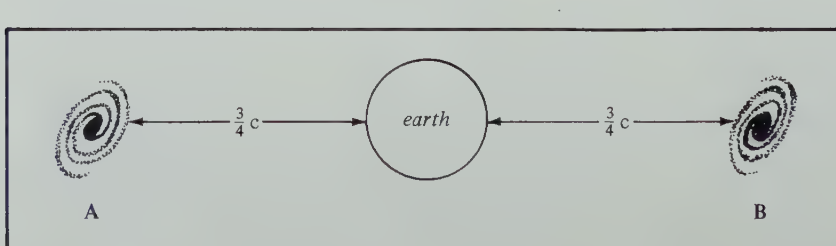
Almost everyone has heard that nothing can travel faster than the speed of light. Some of you, however, may want to challenge this conclusion. Suppose, you may say, you have the situation shown in Figure 22–12. Surely, an observer in galaxy A will see galaxy B going away from him at 1½ times the speed of light! Figure it out for yourself. Where the letter c equals the speed of light, $\frac{3}{4}c + \frac{3}{4}c = 1\frac{1}{2}c$.

Actually the observer in galaxy A will see galaxy B speeding away at only 24/25 the speed of light. This is explained by the theory of relativity developed by Albert Einstein. Although called a theory, most of the predictions of relativity have been thoroughly tested in the laboratory. The theory is accepted as solidly as other laws of physics.

The concepts of relativity seem strange to us because we do not experience the high speeds at which the effects of relativity become noticeable. But in an atom-smashing cyclotron, electrons travel at very high speeds. Relativity predicts that the electrons will become much heavier at high speeds. The cyclotron will not work unless this prediction is taken into account. The electrons *do* behave as though they were much more massive as their speed increases. If they moved with the speed of light, they would behave as if they were infinitely massive.

The theory of relativity was proposed by Einstein to explain, among other things, a very surprising conclusion from careful measure-

FIGURE 22–12
A problem in relativity. The relative speeds of these galaxies as they move apart cannot be added up as you would expect. The speed of one object relative to another cannot exceed **c**.



ment of the velocity of light. This measurement was made in 1887 in Cleveland, Ohio by two Americans, Michelson and Morley. They expected to find that light would go more slowly past the earth when it comes from behind the earth than when it meets the earth from the front. Remember that the earth moves at 30 kilometers per second in its orbit around the sun.

The investigators expected that light would behave like a bullet shot at a moving object such as an airplane. Such a bullet would pass the plane faster if it were shot in the direction of the oncoming plane than if it were shot toward the plane from behind.

Michelson and Morley found that light does not act in this way. The speed of light always remains the same. It is a universal constant. It is equal, in round numbers, to 300,000 kilometers per second. From this one fact alone, a whole series of "Alice in Wonderland" results arise. They can be summed up as follows. The faster you travel, the more massive you get—infinitely massive if you travel with the speed of light. This theory suggests that speeds greater than that of light are impossible. If mass increases to infinity, no force could move it!

And another odd result: the faster you travel, the thinner you get in the direction of your motion. As you approached the speed of light, you would become as thin as paper. And if that isn't enough—the faster you travel, the slower your clock or watch goes. At the speed of light, time ceases to pass!

These happenings in the wonderland of relativity have been tested many times. We cannot escape the results. The length and mass of an object are not definite, fixed quantities. The measurement of length, mass, and time depends on the *speed of the person making the measurements relative to the thing being measured.*

As relative speeds increase, the length of the speeding object shortens (in the direction of motion only). Also, the mass of the speeding object increases (as measured by the "stationary" observer). Remember the actual increased mass of the electrons in the cyclotron, as measured by the "stationary" physicist. Finally, time intervals lengthen. Or the passage of time slows down in a speeding body when compared to the passage of time for the "stationary" observer.

Many people think that relativity is impossible to understand. It is true that some of the ideas of relativity are surprising. But no one should be afraid of an idea because it is surprising. Just think, less than a hundred years ago, how strange the ideas of television, nuclear energy, and radioactive dating of rocks would have seemed to the people of that day. What things do you suppose people a hundred years from now will regard as commonplace that today are unknown to us?

An observer on galaxy A in Figure 22–12 will not see galaxy B going away faster than the speed of light because time and length are relative and not fixed quantities. His measurements of speed (distance divided by time) are changed under the principles of relativity.

22–10 The relativity of time

One of the strangest predictions of relativity concerns the different rates of aging of the

You are in a train at a railway station. Suddenly the train appears to move. Yet, you experience no sensation of motion. Then you realize the train on the next track is sliding past you the other way, while you are standing still.

Einstein (1879–1955) published his special theory of relativity in 1905. It dealt with the problem of what is moving and what is standing still. He suggested that all motion was relative to some chosen frame of reference. This challenged the Newtonian view that motion and rest were absolute. Suddenly, a whole new way of looking at the universe opened up.

Einstein did most of the work that made him famous while employed in the Swiss Patent Office in Zurich, Switzerland. Later he worked at the Institute for Advanced Studies in Princeton.

While formulating the special theory of relativity, Einstein worked out the formula: $E = Mc^2$. Energy equals mass times the square of the speed of light. The interrelationship of mass and energy proved to be fundamental in atomic studies.. When uranium fission was discovered in 1939, Einstein foresaw the possibility of its use in nuclear bombs. He feared that Germany would soon discover this potential and make nuclear weapons. Einstein urged the United States to begin research, but he spent his remaining years working for some world agreement to end the threat of nuclear warfare.

twins, Peter and Paul. Paul stays at home on earth, but Peter travels away from and back to earth at very high speeds. When he returns to earth, Peter finds he is still quite young. But his twin, Paul, is old and gray. The space twin's clocks went more slowly, as well as the rate at which his body aged.

Is this too strange to believe? Well, it has been proved, not by a twin in a rocket, but by measuring the lifetimes of atomic particles called mesons. These patricles are produced by cosmic rays high in the earth's atmosphere. Calculations and experiments on earth indicate that the mesons created high above the earth should

not live long enough to reach the earth's surface. Yet they do. This must mean that since the mesons travel with nearly the speed of light, their "clocks" run very slow. They *do* have time enough to reach the earth on their time scale. Like the traveling twin, they live much longer than the mesons that "stayed at home."

There might be a practical side to the relativity of time. If a rocket ship can be made to move at almost the speed of light, an astronaut could reach the Andromeda galaxy in just 30 years, shipboard time. But when he returned to earth, what a difference he would find. It would be more than four million years later! His historic launching would probably have long been forgotten or have become a part of legendary history.

22–11
Time: the fourth dimension

The idea of an expanding universe may seem hard to grasp. Einstein's Theory of Relativity predicted that the universe should be expanding, even before the red shift was discovered. This strengthens our conviction that it is the expansion that causes the red shift.

To the three dimensions of space we must add a fourth: time. It is as much of a dimension as length. For example, the length of anything can be expressed as the time it takes light to travel that distance. Thus, the moon is 1.3 seconds, light time. The sun's distance can be expressed as 8⅓ light minutes. And the distance to the Andromeda galaxy is about 2 million light years, the time it takes light to travel about 2×10^{19} kilometers. A light beam can be used as a very fine measuring rod, especially for large distances.

When we measure the red shift of a distant galaxy, we must not forget that the light we see right now left that galaxy perhaps hundreds of millions of years ago. The galaxy isn't where we see it. Because of the expansion of the universe, it is "now" much farther out. We won't be able to see the galaxies in the Hydra cluster as they are tonight for another 4 billion years. At that time both we and that cluster of galaxies will be in totally different positions, and conditions.

22–12
The origin of the universe

That we can know anything at all about our complex universe is a tribute to the mind and curiosity of man. We are curious not only about the extent of the universe, but also how it all began. Was it some great accident, or is what we see a part of some great plan?

Suppose we should try to construct a model of everything that can be seen in our most powerful telescopes. One would soon find that it is hopeless to try to make such a model in the classroom. Even if you used the entire United States for your schoolroom, and had your model extend from New York to San Francisco, our solar system would be no larger than a grain of sand.

We may well ask how we can expect a "submicroscopic speck" deep inside that grain of sand to understand how the whole system

started. Present theories of the origin of the universe are based on what we now know about stars and galaxies. The discovery of the expanding universe suggested that maybe the universe started with a "big bang." Billions of years ago the galaxies must have been much closer together than they are now. The "big bang" theory envisions a time when the whole universe was packed together in one huge mass. It exploded, sending the galaxies scurrying outward in all directions (Figure 22–13). If this is so, then this great event must have happened more than ten billion years ago. The theory provides no details of how this might have come about. We as yet know too little about the universe to have precise theories.

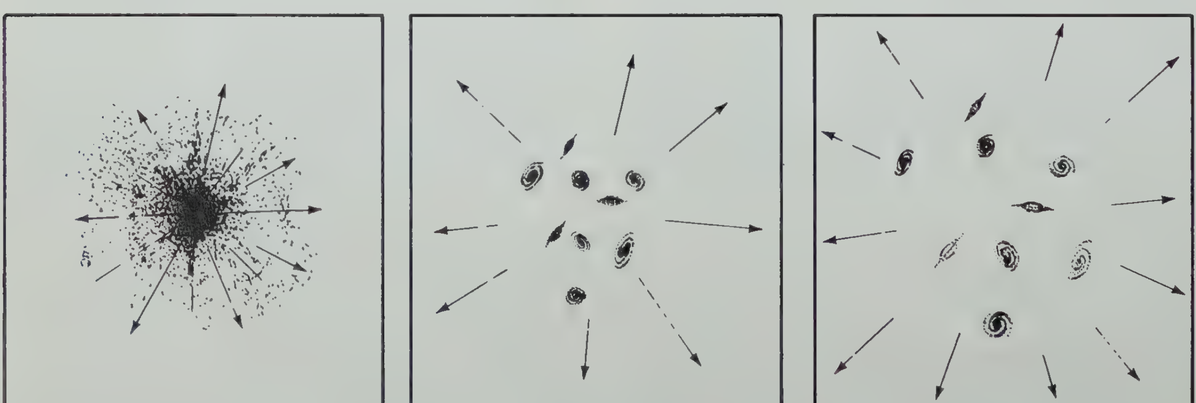
Other astronomers didn't like the "suddenness" of the big bang theory. They proposed that the universe was here all the time. It had no beginning and will have no end. This has been called the "steady state" theory. The galaxies still expand away from each other, but new matter is created in between them which in future ages will form new galaxies.

As new astronomical observations have been made, however, this rather monotonous and continuous universe has just about been abandoned. It doesn't fit the newer facts. The steady state theory predicts that no matter where one looks in the universe, the galaxies should, on the average, be distributed uniformly. But radio telescopes have revealed more galaxies in the distant parts of the universe than should be there.

Still other astronomers believe that there is a compromise between these two theories. They say that the universe really had no beginning and will have no end. There is just a long succession of expansions and contractions—expanding for billions of years and then contracting for billions more. This would be like a huge "breathing in" and "breathing out." One complete "breath" would take about 100 billion years (Figure 22–14).

We can only find out if one of these theories is true by continuing to study and observe the universe. Telescopes placed in space laboratories may help give us the answer. It may also be

FIGURE 22–13
The "big bang" theory of the origin of the universe.



that none of these theories is anywhere near the mark. Our theories may look just as naive to future ages as the theories of Ptolemy and his contemporaries look to us today. But that must not stop us from making theories. A theory is a spur to action. It suggests new observations and experiments to be made, to test the predictions of the theory. These new observations lead in turn to new theories. This is the way scientific knowledge grows.

There are theories, however, of which we are very much more certain than those of the origin of the universe. For example the theory of how the stars manufacture their light and heat has withstood many tests. That theory tells us a great deal about the possible future of man on this earth. It tells us that the sun will shine, much as it has been shining for the past hundreds of millions of years, for hundreds of millions more. The long range weather forecast for the earth for the next four or five billion years is "fair and warmer."

The development of life on earth has taken hundreds of millions of years. Modern man has been on earth for less than a million of these years. He may be at the beginning of hundreds of millions of years to come. Nature gives promise of a long future for mankind, if man himself is wise enough to take this opportunity.

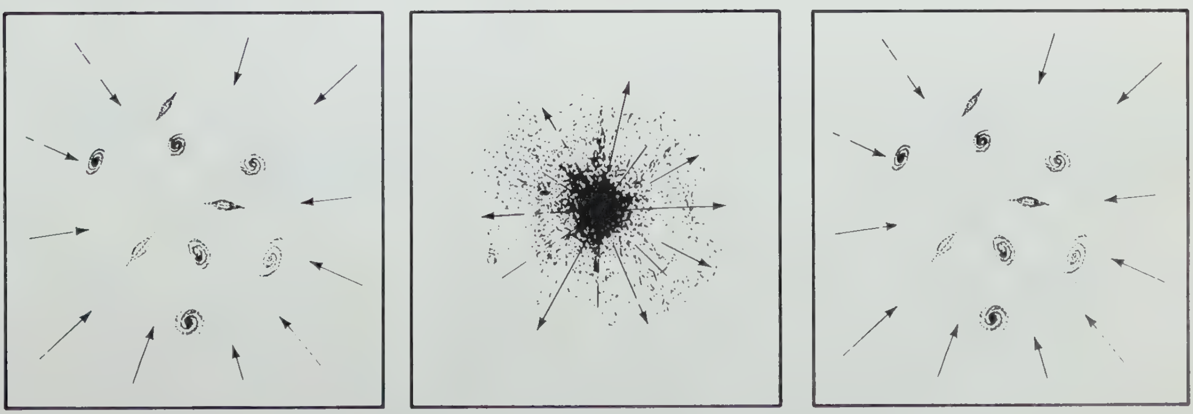
Thought and Discussion

1. According to the theory of relativity, can an object have an absolute mass and length?
2. Can anything really be said to be at rest, or "standing still"?
3. What does moving at 70 miles per hour really mean? Does one always have to say "with respect to what"?

Unsolved Problems

On his deathbed, the famous French mathematician-astronomer, Laplace, is reported to have said: "What we know is but little, what we do not know is immense." This is particularly true when we think about the whole universe, its origin and development, and our place

FIGURE 22–14
The theory of the expanding and contracting universe.



in it. Much work lies ahead before we can say with any certainty how the universe began, how far it extends, and how it will end.

Unsolved problems of less vastness also lie before us. The Milky Way has only begun to be accurately mapped. The richest portions of the Milky Way are observable only from the Southern Hemisphere. Only recently have large telescopes been constructed in that hemisphere. Distances in the Milky Way are still imperfectly known. The distances to galaxies are often uncertain by very large amounts.

How galaxies themselves evolve and change with time is yet unknown. Many types of peculiar galaxies, some of them only recently discovered, present us more mysteries to be solved.

Chapter Review

Summary

Our galaxy, called the Milky Way, contains more than 100 billion stars. The sun occupies a position far from the center of the galaxy. It revolves around it in a period of about 200 million years. Our galaxy is but one of many billions, which vary greatly in size and contents.

The observable universe extends billions of light years in all directions from us. That is how far we can see with our telescopes. The universe appears everywhere to be composed of the same chemical elements we are familiar with on earth. Distant galaxies are rushing away from us as the universe expands. Their speeds increase with their distance from us.

We see back into time as well as out into space. We see a galaxy that is a billion light years away from us with light that left it a billion years ago.

Questions and Problems

A

1. What is the only galaxy we can see "from the outside" using our eyes alone?
2. What things are there in a galaxy besides stars?
3. Suppose two Cepheid variables have the same apparent brightness, but one has twice as long a period of variation as the other. Which one is farther away from us?
4. How many kilometers does the sun travel in one "cosmic year"?
5. Is our galaxy a spiral or an elliptical galaxy?
6. What is the importance of Cepheid variables to the astronomer?

B

1. Why are the constellations of the summer sky different from those in the winter?
2. If two stars appear to have exactly the same brightness yet one is actually 100 times brighter than the other, how much farther away is it?
3. The farther out in space a celestial object is, the farther back in time it appears to us. Is this a way in which time can be considered a fourth dimension?

4. Discuss man's possible future on earth. How much time does the sun "give" the human race? What sort of things could cut this future short? What control does man have over his future?
5. Call one round trip of the sun around the galaxy a "cosmic year." What kind of life was there on the earth 5 cosmic years ago? ten cosmic years ago?

C

1. An astronomer observes a galaxy to have a "red shift" of 0.10. What is the speed of the galaxy? Is it moving toward or away from us? The formula is: speed of object = wavelength shift x speed of light.
2. Suppose we were looking at the earth's path from a place some distance from the solar system. What would the earth's orbit look like to us then? Diagram the path of the earth as seen from outer space. (Keep in mind that while the earth travels 30 kilometers in one second in its journey around the sun, it travels with the sun some 250 kilometers in that same second of time.)
3. Light travels with the speed of light, of course. Does this mean that a beam of light takes no time (according to its own "wristwatch") to go from the Milky Way to the Andromeda galaxy?
4. The origin of everything we see about us on earth and in the universe was probably the element hydrogen. Where do you think the hydrogen came from?
5. Think of the suns' orbit around the galaxy. The sun moves 250 kilometers per second. Even so, its orbit is so large that it takes over 200 million years to make one complete circuit. Try to prove the following statement. The center-line of a straight superhighway is no straighter over a mile's length than is the sun's orbit around the galaxy in a year's time. (Hint: assume that the center line of the highway does not vary more than a few inches in the course of a mile.)
6. In a science fiction story a message was sent from one civilization to another across the far reaches of our galaxy. It was described as "the long-since-dead talking to the not-yet-born." What did that statement mean?

Suggested Readings

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Appendix A Mathematical Information

A-Part 1 Powers of Ten

In earth science it is often necessary to use very large and very small numbers. The area of the earth's surface is 361,000,000 square kilometers. A convenient shorthand for writing numbers like this one is to use powers of ten. For example,

Number	Equivalent Power of 10	Number	Equivalent Power of 10
$1{,}000 =$	1×10^3	$0.1 = \frac{1}{10^1} =$	1×10^{-1}
$100 =$	1×10^2	$0.01 = \frac{1}{10^2} =$	1×10^{-2}
$10 =$	1×10^1	$0.001 = \frac{1}{10^3} =$	1×10^{-3}
$1 =$	1×10^0	$0.0001 = \frac{1}{10^4} =$	1×10^{-4}

Thus, 361,000,000 is the same as 3.61 times 100,000,000. Since this is 3.61 times $10 \times 10 \times 10 \times 10 \times 10 \times 10 \times 10 \times 10$ or 3.61 multiplied by 10 eight times, we call this 3.61×10^8.

$$\text{coefficient} \rightarrow 3.61 \times 10^{8} \;\; \begin{matrix} \swarrow \text{exponent} \\ \nwarrow \text{base} \end{matrix}$$

The **exponent** tells how many times to multiply by 10, which is called the **base**. To convert a number from the usual long form to the standard form, move the decimal point to the left until you have a number between one and ten. The number of places that you moved the decimal point is the exponent, or power of ten. The coefficient is the number between one and ten used with the power of ten. In the example, the decimal point was moved eight places to the left, so the exponent is 8. The base is 10 since we are using the decimal number system. The coefficient is 3.61.

If the original long number is less than one, it can be expressed as a number between one and ten divided by ten to some power.

$$0.008 = 8 \times \frac{1}{1{,}000} = 8 \times \frac{1}{10^3} = 8 \times 10^{-3}$$

That is, if you have to move the decimal point to the *right* to get a number between 1 and 10, the exponent has a negative sign.

A-Part 2 Metric and Other Units of Measure

The Metric System

Prefixes

PREFIX	MEANING
kilo-	1,000 or 10^3
centi-	0.01 or 10^{-2}
milli-	0.001 or 10^{-3}

Units of Length

1 kilometer (km) = 1,000 meters (m) = 10^3 m

1 centimeter (cm) = 0.01 m = 10^{-2} m

1 millimeter (mm) = 0.001 m = 10^{-3} m

1 angstrom (Å) = 0.0000000001 m = 10^{-10} m

Units of Area

1 square meter (m^2) = 10,000 square centimeters (cm^2) = 100 cm × 100 cm

Units of Volume

1 cubic meter (m^3) = 1,000,000 cubic centimeters (cc) = 100 cm × 100 cm × 100 cm

1 liter (l) = 1,000 milliliters

1 milliliter (ml) = 1 cc

Units of Mass

1 metric ton = 1,000 kilograms

1 kilogram (kg) = 1,000 grams

1 gram (g) = approximately the weight of 1 cc of water

1 milligram (mg) = 0.001 g

Units of Time

1 hour (hr) = 60 minutes (min) = 3,600 seconds (sec)

METRIC-ENGLISH EQUIVALENTS
(Values are approximate)

Length

1 kilometer = 0.621 mile (1 mile = 1.610 km)

1 meter = 1.094 yards = 3.281 feet (1 foot = 0.305 m)

1 centimeter = 0.3937 inch (1 inch = 2.54 cm)

1 millimeter = 0.0394 inch or approximately 1/25 inch (1 inch = 25.4 mm)

Volume

1 cubic meter = 1.31 cubic yards (1 cubic yard = 0.76 m^3)

1 liter = 1.06 quarts (1 quart = 0.95 l)

Mass

1 kilogram = 1,000 g = 2.20 pounds (1 pound = 0.45 kg)

1 metric ton = 1.1 tons (U.S.) (1 U.S. ton = 0.909 metric ton)

OTHER FREQUENTLY USED UNITS OF MEASURE

Distance

1 Astronomical Unit (A.U.) = 149.6×10^6 km (mean distance from earth to sun)

1 light-year = 9.46×10^{12} km or 5.88×10^{12} miles

Force

1 dyne (d) = the force that will produce an acceleration of 1 centimeter/second^2 when applied to a 1-gram mass.

1 newton (N) = the force that will produce an acceleration of 1 meter/second^2 when applied to a 1-kilogram mass.

1 N = 100,000 d

Work

1 erg = the work done by a force of 1 dyne when its point of application moves through a distance of 1 centimeter in the direction of the force.

Angle Measurement

1 degree (1°) = 1/360 of a circle = 60 minutes

1 minute (1′) = 60 seconds (60″)

Heat

1 calorie (cal) = the amount of heat that will raise the temperature of 1 gram of water 1°C with the water at 15°C.

Pressure

1 millibar (mb) = 1,000 d/cm^2

Average atmospheric pressure at sea level = 1,013.25 mb

A-Part 3
Relative and Percentage Error

If you divide the difference between your answer to a problem and the correct answer by the correct answer, you obtain the **relative error.** If you multiply the relative error by 100, you obtain the **percentage error.** For example, in Investigation 1–2 you calculate the circumference of the earth. If you consider the actual

value of the earth's circumference to be 40,000 km and your measurement was 38,000 km, the difference between them is 2,000 km. Dividing this difference (2,000 km) by the actual value (40,000 km) gives a relative error of 0.05 $\left(\frac{2,000}{40,000} = \frac{1}{20} = 0.05\right)$. Multiplying this relative error by 100 gives a percentage error of 5% ($0.05 \times 100 = 5\%$). A student who obtained a measured value of 42,000 km would have the same percentage error as your value of 38,000 km. Can you see why?

It is often desirable to calculate the percentage error to see if your answer is reasonable in relation to the possible sources of error of your instruments and measurements. If all your measuring instruments are reasonably accurate and your answer has a percentage error of 40%, you should review your work and look for errors. If, however, your measuring instruments are crude and your percentage error is only 8% or so, then it is likely that your work is as accurate as your instruments will permit. As a general rule, the greater your percentage error, the more carefully you should recheck your work for mistakes.

Appendix B Weather Data

B-Part 1
Recording Weather Watch Data (Investigation 3–2)

Your teacher will provide you with the necessary wall chart on which to record your data for this investigation. Gather data carefully to avoid errors that might affect your analysis of the data later. Record data legibly on the chart.

The specific information to be gathered as part of the investigation includes:

1. **Date.** Record the day of the month at the top of each column.

2. **Time.** Record the exact time your observation is made. Use the 24-hour clock notation. In this notation, 10:15 A.M. is 1015 and 9:02 P.M. is 2102. The hours after noon (P.M.) are numbered from 1300 to 2400.

3. **Air Temperature.** A thermometer is commonly used to measure air temperature. Air temperature can also be measured by a thermograph, a thermometer that automatically records air temperature on a continuous graph attached to a rotating drum. Temperatures should be measured outdoors in a shaded shelter about 1.5 meters (5 feet) above the ground. The thermometer bulb should be kept dry and the air should be free to circulate through the shelter. All temperatures should be recorded in degrees Fahrenheit. (See Appendix B, Part 2.)

4. **Atmospheric Pressure.** Air pressure can be measured with an aneroid or mercurial barometer or by a barograph. A barograph, like a thermograph, records air pressure on a sheet of paper attached to a revolving drum. Unlike the thermometer or thermograph, the barometer or barograph can be placed indoors. Air pressure should be measured and recorded in millibars. Use Figure 1 to convert millibars to inches of mercury.

5. **Wind.** Both wind direction and speed are needed in this observation. Record wind direction and speed along with sky condition for each day on your wall chart. **Wind direction** can be measured with a wind vane or some means you can devise. It is recorded on the chart by a line representing the compass direction *from* which the wind is blowing, with north at the top of the chart.

Wind speed can be measured with an anemometer or a wind speed meter. If neither is available, you can observe local conditions and estimate the velocity of the wind from Figure 2. The "flags" indicating the wind speed as shown on the daily weather maps should be drawn on the end of your wind direction line—the end from which the wind is blowing.

An explanation of symbols and entries on weather maps is published by the National Oceanic and Atmospheric Administration. You can also refer to *Weather Maps: How They are Made and Used* by Miles F. Harris and John O. Ellis (ESCP Reference Series, RS–10).

6. **Sky Condition.** This observation includes the amount of the sky covered by clouds and the type of cloud. For ease of recording, determine if the sky is clear, partly cloudy, or cloudy. Use the symbols in Figure 3 for your three categories. The type of cloud should be noted as billowy or sheet-like. Sketch the type of cloud on the chart as simply as possible.

7. **Weather.** Observe and enter on the chart

Figure 1 *Conversion of Millibars to Inches of Mercury*

Mb	Inches	Mb	Inches	Mb	Inches	Mb	Inches	Mb	Inches	Mb	Inches
940	27.76	960	28.35	980	28.94	1000	29.53	1020	30.12	1040	30.71
941	27.79	961	28.38	981	28.97	1001	29.56	1021	30.15	1041	30.74
942	27.82	962	28.41	982	29.00	1002	29.59	1022	30.18	1042	30.77
943	27.85	963	28.44	983	29.03	1003	29.62	1023	30.21	1043	30.80
944	27.88	964	28.47	984	29.06	1004	29.65	1024	30.24	1044	30.83
945	27.91	965	28.50	985	29.09	1005	29.68	1025	30.27	1045	30.86
946	27.94	966	28.53	986	29.12	1006	29.71	1026	30.30	1046	30.89
947	27.96	967	28.56	987	29.15	1007	29.74	1027	30.33	1047	30.92
948	27.99	968	28.58	988	29.18	1008	29.77	1028	30.36	1048	30.95
949	28.02	969	28.61	989	29.21	1009	29.80	1029	30.39	1049	30.98
950	28.05	970	28.64	990	29.23	1010	29.83	1030	30.42	1050	31.01
951	28.08	971	28.67	991	29.26	1011	29.85	1031	30.45	1051	31.04
952	28.11	972	28.70	992	29.29	1012	29.88	1032	30.47	1052	31.07
953	28.14	973	28.73	993	29.32	1013	29.91	1033	30.50	1053	31.10
954	28.17	974	28.76	994	29.35	1014	29.94	1034	30.53	1054	31.12
955	28.20	975	28.79	995	29.38	1015	29.97	1035	30.56	1055	31.15
956	28.23	976	28.82	996	29.41	1016	30.00	1036	30.59	1056	31.18
957	28.26	977	28.85	997	29.44	1017	30.03	1037	30.62	1057	31.21
958	28.29	978	28.88	998	29.47	1018	30.06	1038	30.65	1058	31.24
959	28.32	979	28.91	999	29.50	1019	30.09	1039	30.68	1059	31.27

Figure 2 *Beaufort Wind Scale*

Beaufort Number	Name	Effects of wind at various speeds	Wind speed	
			mph	*knots*
0	Calm	Smoke rises vertically	Under 1	Under 1
1	Light air	Wind direction shown by smoke drift	1–3	1–3
2	Light breeze	Wind felt on face; leaves rustle; ordinary vane moved by wind	4–7	4–6
3	Gentle breeze	Leaves and twigs in constant motion; wind extends light flag	8–12	7–10
4	Moderate breeze	Dust and loose paper; small branches are moved	13–18	11–16
5	Fresh breeze	Small trees in leaf begin to sway	19–24	17–21
6	Strong breeze	Large branches in motion	25–31	22–27
7	Moderate gale	Whole trees in motion	32–38	28–33
8	Fresh gale	Twigs broken off trees; progress generally impeded	39–46	34–40
9	Strong gale	Slight structural damage occurs	47–54	41–47
10	Whole gale	Trees uprooted; considerable structural damage	55–63	48–55
11–17	Hurricane	Very rarely experienced; widespread damage	64–136	56–118

the state of the weather at the time of observation, such as rain, snow, thunderstorms, clear, cloudy, fog, haze, smog, and so forth.

8. **Precipitation.** Moisture that has fallen to the earth's surface in the form of rain, hail, drizzle, sleet, or snow is considered to be precipitation. Dew or fog is not. Precipitation is recorded as the quantity of water deposited in the gauge since the last reading. If the gauge has snow in it, melt the snow to secure a liquid reading.

B-Part 2 Temperature Measurement and Scales

Temperature is a measure of the amount of molecular activity in a substance. If molecules are moving slowly, the temperature of the substance containing them is said to be low. If molecular motion is rapid, the temperature is high. In general, when the temperature of a substance is high, the substance tends to expand; when cooled, the substance contracts.

Thermometers are marked (calibrated) with a scale. Scales that are commonly used are Fahrenheit and Celsius. The Fahrenheit scale is used in the United States for public weather information. The Celsius scale is sometimes called centigrade, because there are 100 divisions between the freezing and boiling points of water. The Celsius scale is widely used for temperature measurement throughout the world. It is also used for practically all scientific work in the United States.

A third scale for temperature measurement, useful in some kinds of scientific work, is the Kelvin scale, called an absolute scale because the zero point is that point at which there is no molecular motion. Kelvin scale divisions are the same size as Celsius divisions; the Kelvin zero is 273 degrees below the Celsius zero.

You can convert the temperature reading on one scale to the reading on another scale if you take into account the size of the degrees and the zero point. For example, as indicated below, Kelvin temperature is found by adding 273 degrees to Celsius temperature. Remember that the degrees are the same size but counting starts at different places in the two scales. Converting Celsius temperature to Fahrenheit requires adjusting for different sizes of degrees and different starting points. You can convert from one to the other by using the following formulas.

To change from Fahrenheit (F) to Celsius (C)

$$°C = \frac{(°F - 32)}{1.8}$$

To change from Celsius (C) to Fahrenheit (F)

$$°F = (°C \times 1.8) + 32$$

To change from Celsius (C) to Kelvin (K)

$$°K = °C + 273$$

There is also an easier method of finding the temperature on one scale that is nearly equiva-

FIGURE 3
Symbols for sky condition.

Sky Condition	Cloud Cover	Symbol
Cloudy	*More than eight-tenths of sky covered.*	●
Partly cloudy	*Two-tenths to eight-tenths of sky covered.*	◑
Clear	*Less than two-tenths of sky covered.*	○

lent to the temperature on another scale. Figure 4 shows a thermometer marked with the three scales. To find the approximate equivalent temperature in other scales, move directly across the page from one scale to another.

B-Part 3
Finding the Dew-point Temperature and the Relative Humidity.

The dew point can also be obtained by using a **psychrometer.** This instrument measures indirectly the amount of latent heat that would be required to produce saturation. The sling psychrometer consists of two thermometers. One (the **dry-bulb**) is an ordinary glass thermometer. The other (the **wet-bulb**) has its bulb covered with a piece of muslin. The muslin must be soaked with pure (distilled) water just before the measurement is made. Then the psychrometer is whirled until the wet-bulb temperature stops falling.

The difference between the dry- and the wet-bulb temperatures is called the **wet-bulb depression.** It is a measure of the amount of energy needed to evaporate enough water to produce saturation at the wet-bulb temperature. If you know the dry-bulb temperature and the wet-bulb depression you can find the dew point and the relative humidity. The examples in Figure 6 will help you learn how to use Figure 5.

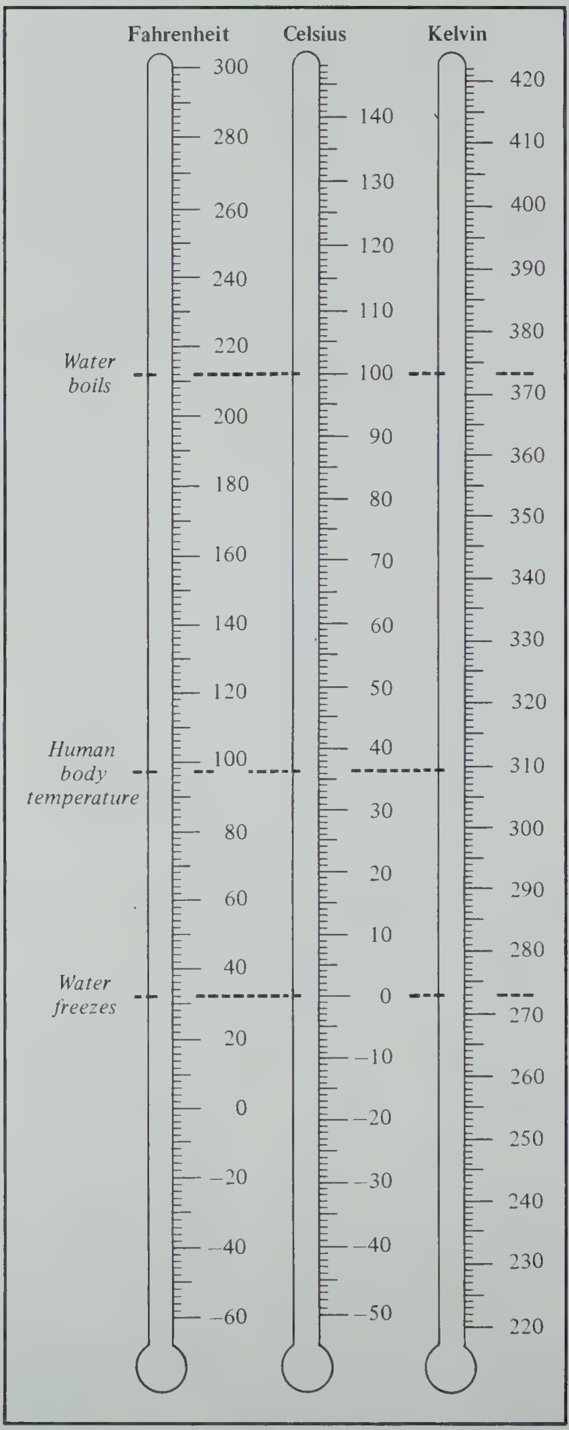
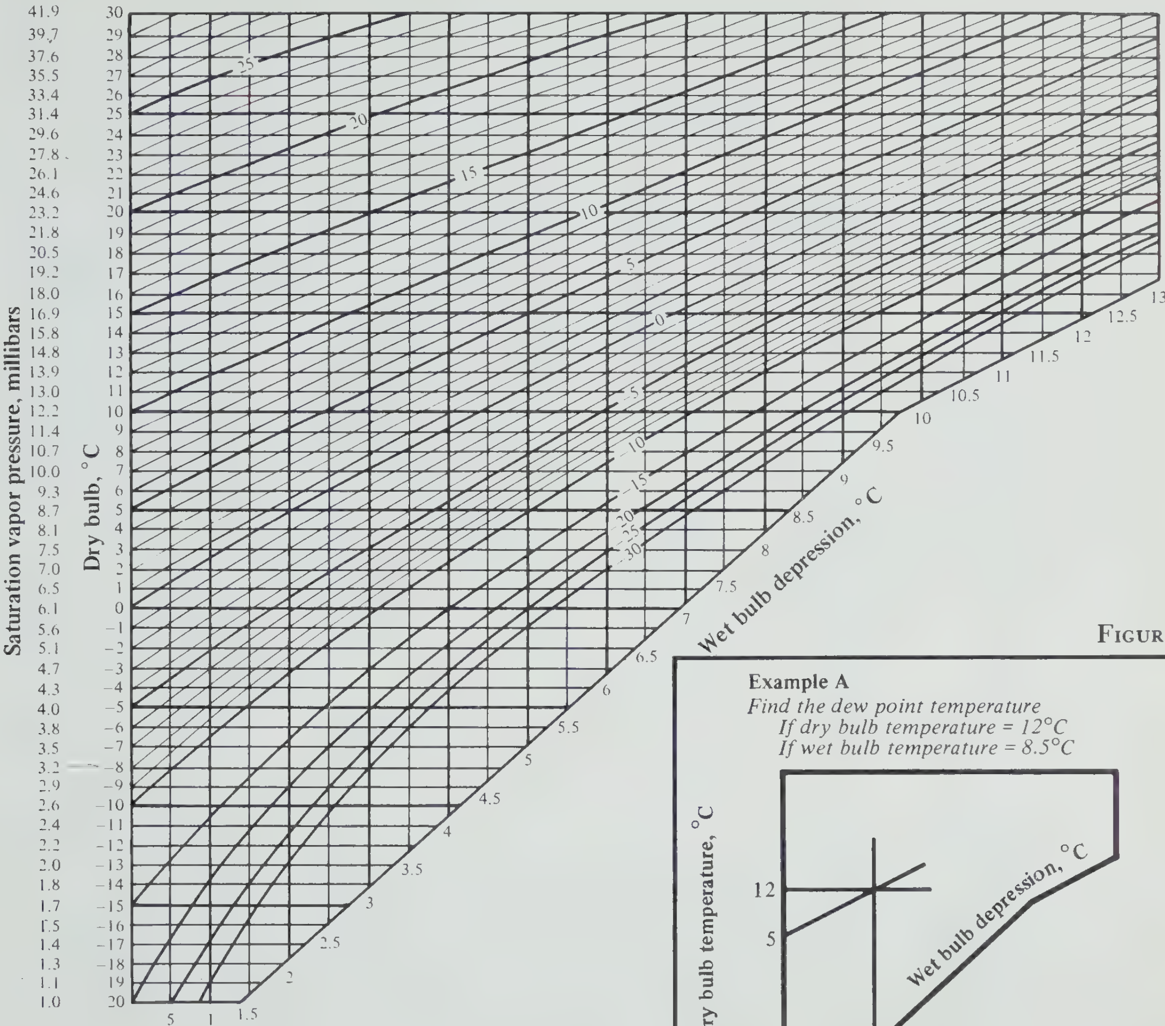


FIGURE 4
Comparison of Fahrenheit, Celsius, and Kelvin temperature scales.

FIGURE 5 *Dew-point temperature chart.*



1. To find the dew-point temperature (See Example A): Find the dry-bulb temperature along the left side of the chart (12°C). Follow horizontal line to the vertical line for the wet-bulb depression (difference between dry-bulb and wet-bulb temperatures, or 3.5°C). Read the dew-point temperature from sloping line at this intersection (5°C).
2. To find the relative humidity (See Example B): Read the value of the saturation vapor pressure for the dry-bulb temperature at left side of chart. (13.9 mb is saturation vapor pressure for air at 12°C). Read the value of saturation vapor pressure for dew-point temperature also at the left side of chart. (8.7 mb is saturation vapor pressure for air at 5°C.) Divide the second value (8.7) by the first (13.9) and multiply by 100. Answer: 63%

FIGURE 6

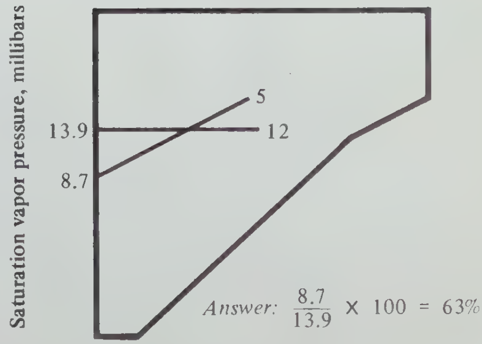
Example A

Find the dew point temperature
If dry bulb temperature = 12°C
If wet bulb temperature = 8.5°C

Answer: 5°C

Example B

Find the relative humidity
If dry bulb temperature = 12°C
If wet bulb temperature = 8.5°C



Answer: $\frac{8.7}{13.9} \times 100 = 63\%$

Appendix C Minerals and Elements

Part 1
Properties of Some Minerals

Mineral Name	Color	Streak*	Luster	Hardness†	Composition	Remarks
apatite	green or brown	white	glassy	5	$Ca_5(F,Cl,OH)(PO_4)_3$	used in making fertilizer
biotite	black	colorless	glassy, shining	2½–3	$K(Mg,Fe)_3Al\text{-}Si_3O_{10}(OH)_2$	black mica, fractures in very thin plates
calcite	colorless, white	colorless	glassy, pearly	3	$CaCO_3$	rock-forming mineral
cinnabar	red	bright red	glassy, earthy	2–2½	HgS	mercury ore
corundum	brown, pink, blue	none	sparkling, dull	9	Al_2O_3	gem stone, used as an abrasive
diamond	grayish-black	none	sparkling, dull	10	C	gem stone, industrial saws
feldspar	white, gray, flesh-red	white	glassy	6	$CaAl_2Si_2O_8$ $NaAlSi_3O_8$ $KAlSi_3O_8$	common rock-forming minerals
fluorite	light purple, yellow, green	colorless	glassy	4	CaF_2	used in steel and glassmaking
galena	lead gray	gray-black	metallic	2½	PbS	lead ore
graphite	steel gray to iron black	black to gray-black	metallic, earthy	1–2	C	feels greasy, used as a lubricant
gypsum	colorless, white, gray	colorless	silky	2	$CaSO_4 \cdot 2H_2O$	used in making plaster of Paris
halite	white, red, blue	colorless	translucent glassy,	2½	NaCl	common salt, tastes salty
hornblende	dark green to black	colorless to gray	glassy	5–6	$NaCa_2(Mg,Fe)_5\text{-}(Si,Al)_8O_{22}\text{-}(O,OH)_2$	an amphibole, a common rock mineral
magnetite	iron black	black	metallic	5½–6	Fe_3O_4	magnetic
muscovite	tan, green, yellow, white	colorless	glassy, silky	2–2½	$KAl_3Si_3O_{10}\text{-}(OH)_2$	white mica, flakes in thin sheets
olivine	olive to gray, green, brown	colorless	glassy	6½–7	$(Mg,Fe)_2SiO_4$	green rock-forming mineral

Mineral Name	Color	Streak*	Luster	Hardness†	Composition	Remarks
pyrite	pale brass, yellow	green or brown-black	metallic	6–6½	FeS_2	"fool's gold"
pyroxene	black, dark green	black or dark green	glassy, dull	5–6	$Ca(Mg,Fe)Si_2O_6$	accessory in igneous rocks
quartz	colorless, white	none	glassy	7	SiO_2	gem stone, common rock-forming mineral
talc	white, green, gray	colorless	glassy, pearly	1	$Mg_3Si_4O_{10}(OH)_2$	greasy feel, used in talcum powder
topaz	yellow, pink, blue, green	none	glassy	8	$Al_2SiO_4(F,OH)_2$	gem stone

Notes for C-Part 1

**Streak*

The color of the fine powder left after a mineral has been rubbed on a piece of unglazed porcelain (streak plate) is known as its streak. This is useful in the identification of minerals, because the color of a mineral's streak is usually constant.

†Hardness

The resistance that a mineral surface offers to scratching is its hardness.

To determine the hardness of any mineral, it is necessary to find which of the minerals in Mohs' scale of hardness it can scratch and which it cannot scratch.

Mohs' Hardness Scale

1. Talc 2. Gypsum 3. Calcite 4. Fluorite
5. Apatite 6. Orthoclase 7. Quartz
8. Topaz 9. Corundum 10. Diamond

C-Part 2
The Elements

(Listed alphabetically with the atomic number preceding them)

89 Actinium (Ac)
13 Aluminum (Al)
95 Americium (Am)
51 Antimony (Sb)
18 Argon (Ar)
33 Arsenic (As)
85 Astatine (At)
56 Barium (Ba)
97 Berkelium (Bk)
4 Beryllium (Be)
83 Bismuth (Bi)
5 Boron (B)
35 Bromine (Br)
48 Cadmium (Cd)
20 Calcium (Ca)
98 Californium (Cf)
6 Carbon (C)
58 Cerium (Ce)
55 Cesium (Cs)
17 Chlorine (Cl)
24 Chromium (Cr)
27 Cobalt (Co)
29 Copper (Cu)
96 Curium (Cm)
66 Dysprosium (Dy)
99 Einsteinium (Es)
68 Erbium (Er)
63 Europium (Eu)
100 Fermium (Fm)
9 Fluorine (F)
87 Francium (Fr)
64 Gadolinium (Gd)
31 Gallium (Ga)
32 Germanium (Ge)
79 Gold (Au)
72 Hafnium (Hf)
2 Helium (He)
67 Holmium (Ho)
1 Hydrogen (H)
49 Indium (In)
53 Iodine (I)
77 Iridium (Ir)
26 Iron (Fe)
36 Krypton (Kr)
57 Lanthanum (La)
103 Lawrencium (Lw)
82 Lead (Pb)
3 Lithium (Li)
71 Lutetium (Lu)
12 Magnesium (Mg)
25 Manganese (Mn)
101 Mendelevium (Md)
80 Mercury (Hg)
42 Molybdenum (Mo)
60 Neodymium (Nd)
10 Neon (Ne)
93 Neptunium (Np)
28 Nickel (Ni)
41 Niobium (Nb)
7 Nitrogen (N)
102 Nobelium (No)
76 Osmium (Os)
8 Oxygen (O)
46 Palladium (Pd)
15 Phosphorus (P)
78 Platinum (Pt)
94 Plutonium (Pu)
84 Polonium (Po)
19 Potassium (K)
59 Praseodymium (Pr)
61 Promethium (Pm)
91 Protactinium (Pa)
88 Radium (Ra)
86 Radon (Rn)
75 Rhenium (Re)
45 Rhodium (Rh)
37 Rubidium (Rb)
44 Ruthenium (Ru)
62 Samarium (Sm)
21 Scandium (Sc)
34 Selenium (Se)
14 Silicon (Si)
47 Silver (Ag)
11 Sodium (Na)
38 Strontium (Sr)
16 Sulfur (S)
73 Tantalum (Ta)
43 Technetium (Tc)
52 Tellurium (Te)
65 Terbium (Tb)
81 Thallium (Tl)
90 Thorium (Th)
69 Thulium (Tm)
50 Tin (Sn)
22 Titanium (Ti)
74 Tungsten (W)
92 Uranium (U)
23 Vanadium (V)
54 Xenon (Xe)
70 Ytterbium (Yb)
39 Yttrium (Y)
30 Zinc (Zn)
40 Zirconium (Zr)

Appendix D Data for Investigation 3-3

Seismic data from September 1968 through February 1969

(Obtained from U.S. Coast and Geodetic Survey, Rockville, Maryland)

DATE	LAT.	LONG.	DEPTH (km)
SEPTEMBER			
12	16.8 S	71.0 W	114
14	36.3 N	69.8 E	193
15	22.7 S	171.5 E	86
16	6.6 S	149.2 E	3
17	17.3 S	167.7 E	24
17	45.2 N	12.7 E	43
18	16.0 S	167.4 E	44
18	10.6 S	166.0 E	144
23	36.4 N	40.7 E	31
25	21.2 S	69.8 W	129
25	15.8 N	92.0 W	155
26	4.7 S	139.3 E	14
27	3.8 S	143.5 E	12
27	29.9 S	71.5 W	73
28	12.2 N	89.1 W	51
29	3.7 S	143.3 E	39
29	3.7 S	143.4 E	38
29	33.0 S	179.1 W	15
OCTOBER			
3	3.8 S	143.3 E	49
3	18.3 N	94.8 E	30
3	19.6 N	122.0 E	40
7	3.2 S	146.1 E	19
7	26.3 N	140.8 E	496
7	61.4 N	150.3 W	55
8	35.7 N	139.5 E	103
9	14.8 N	96.7 W	9
12	6.1 S	152.2 E	14
12	31.4 N	141.5 E	52

DATE	LAT.	LONG.	DEPTH (km)
17	11.7 N	61.6 W	124
17	28.4 S	177.0 W	151
19	7.0 S	147.4 E	87
19	32.7 S	72.0 W	35
21	5.4 S	146.5 E	170
21	35.8 N	140.6 E	17
21	38.0 N	122.3 W	4
22	6.8 N	72.9 W	161
22	17.6 S	179.1 W	621
23	59.8 N	150.4 W	42
26	8.9 S	110.9 E	52
26	17.2 N	97.8 W	40
26	64.8 N	147.5 W	10
27	5.9 N	125.6 E	193
27	15.1 S	72.4 W	133
28	27.3 N	86.1 E	37
30	65.3 N	149.9 W	5
30	65.4 N	149.9 W	3
31	14.0 N	90.8 W	81
31	61.1 N	145.8 W	50
NOVEMBER			
1	41.6 S	175.0 E	29
2	1.5 N	126.2 E	37
2	19.0 S	169.0 E	150
3	4.8 S	152.8 E	65
3	5.5 S	145.6 E	54
3	38.6 N	29.7 E	12
4	16.2 S	73.0 W	101
5	8.8 S	115.0 E	98
5	29.5 N	139.5 E	371

Date	Lat.	Long.	Depth (km)
NOVEMBER			
6	23.9 S	67.7 W	122
6	31.7 N	50.7 E	42
6	39.0 N	23.5 E	21
6	40.3 N	143.6 E	9
6	41.2 N	143.1 E	48
7	40.2 N	142.3 E	61
7	45.0 N	150.0 E	59
7	54.3 N	164.6 W	46
7	59.1 S	24.9 W	146
7	60.2 N	153.0 W	145
8	6.9 S	129.2 E	150
8	18.8 S	169.5 E	244
10	19.9 S	169.8 E	259
10	34.8 N	24.3 E	33
10	44.8 N	146.7 E	145
11	19.6 S	179.1 W	674
13	35.8 N	26.2 E	123
14	31.7 N	131.7 E	21
14	65.7 N	150.0 W	21
15	51.4 N	178.7 E	74
17	19.6 S	177.8 W	458
17	39.5 N	111.0 W	6
18	26.8 N	92.3 E	72
18	36.5 N	140.5 E	55
19	33.2 S	179.2 W	49
21	5.1 S	151.7 E	63
23	14.4 N	92.2 W	115
23	18.4 S	168.2 E	97
24	21.6 S	170.6 E	142
26	4.9 S	152.1 E	135
26	21.3 S	170.0 E	78
26	45.7 N	28.1 E	28
27	4.2 S	151.5 E	36
28	7.5 S	155.9 E	82
29	5.7 S	76.9 W	110
30	46.5 N	122.4 W	13
DECEMBER			
2	6.9 N	73.4 W	153
4	1.3 S	78.4 W	31
4	3.7 N	76.1 W	75
6	14.9 S	167.3 E	145
8	6.1 N	72.2 W	64
8	13.9 N	90.6 W	116
8	28.6 S	71.4 W	36
8	32.3 S	71.4 W	65
8	36.5 N	71.0 E	187
9	7.1 S	130.1 E	131
9	51.8 N	176.8 W	62
9	57.7 N	153.9 W	153
10	2.7 N	83.3 W	24
10	6.3 S	130.4 E	107
10	5.5 S	151.8 E	71
10	6.8 N	72.9 W	164
10	13.2 N	89.6 W	69
10	14.1 S	166.7 E	30
11	12.0 N	125.5 E	12
11	51.7 N	176.2 W	65
11	23.9 S	176.1 W	95
12	16.4 N	122.2 E	50
14	59.4 N	152.9 W	106
14	33.5 S	178.6 W	96
14	60.0 N	152.4 W	77
15	20.6 S	178.0 W	470
16	7.1 N	82.2 W	16
16	17.9 S	67.0 W	283
16	36.0 N	71.0 E	103
17	25.2 S	180.0	505
17	60.1 N	156.6 W	115
17	60.2 N	152.8 W	86
17	63.1 N	150.6 W	118
18	6.1 S	148.7 E	74
18	21.4 S	67.3 W	187
18	40.9 N	142.9 E	57
19	5.0 N	126.9 E	65
19	59.9 N	152.6 W	34
19	60.0 N	152.7 W	110
21	36.6 N	27.1 E	17
22	20.3 S	178.0 W	527
22	33.5 S	177.0 W	39
23	1.7 N	126.6 E	36

Date	Lat.	Long.	Depth (km)
DECEMBER			
24	30.6 S	178.3 W	130
25	30.7 S	178.1 W	43
25	58.7 N	153.8 W	81
27	29.5 S	177.8 W	48
28	5.4 S	152.6 E	58
28	63.0 N	148.2 W	80
29	5.2 S	151.8 E	65
JANUARY			
1	24.9 S	179.2 E	657
3	24.5 S	176.2 W	68
3	18.5 N	65.1 W	113
3	6.9 S	125.3 E	527
4	57.9 N	153.9 W	61
5	8.9 S	123.5 E	466
5	48.4 N	146.1 E	61
6	11.4 N	87.2 W	33
6	22.5 S	179.2 E	586
6	24.7 S	68.0 W	97
7	38.5 N	20.1 E	15
8	22.7 S	68.3 W	111
9	7.8 S	158.7 E	31
9	34.9 N	140.3 E	23
10	15.0 S	175.4 W	106
10	16.1 S	169.7 E	24
11	28.4 S	177.0 W	68
11	28.5 S	176.8 W	68
12	7.1 S	146.3 E	188
12	23.3 S	179.6 E	697
13	34.7 N	25.2 E	47
13	38.3 N	22.6 E	51
14	18.5 N	145.3 E	221
14	20.2 S	175.8 W	16
17	16.3 S	73.5 W	62
20	7.4 S	128.3 E	125
21	8.8 S	124.1 E	16
22	35.7 N	70.0 E	141
25	0.8 N	126.1 E	24
25	3.8 S	35.7 E	34
26	5.8 S	153.8 E	26
26	8.3 S	119.0 E	69
26	25.1 N	122.6 E	146
26	38.2 N	73.8 E	138
27	20.5 S	169.6 E	46
27	30.6 S	177.2 W	24
28	14.8 S	173.4 W	13
29	5.2 N	76.0 W	109
29	11.4 S	166.4 E	153
29	24.6 N	121.8 E	77
30	4.0 N	123.0 E	521
30	42.8 N	145.3 E	8
31	4.0 N	127.9 E	64
FEBRUARY			
1	17.8 N	145.9 E	115
3	3.5 N	128.3 E	118
3	15.4 S	75.8 W	64
3	19.2 N	121.2 E	57
3	25.7 S	178.3 E	654
5	15.8 S	73.0 W	113
6	51.6 N	176.2 W	58
7	40.4 N	124.5 W	6
8	6.9 N	73.1 W	157
10	19.3 N	155.1 W	10
11	19.3 N	177.6 W	424
11	6.7 S	126.8 E	450
17	3.8 N	128.4 E	14

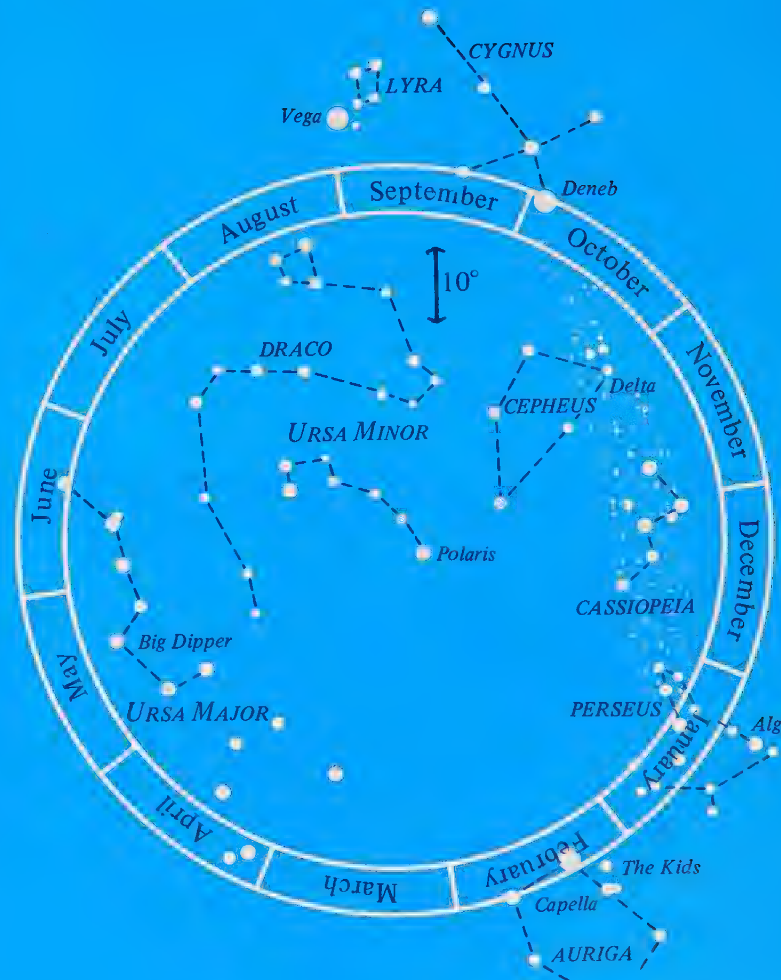
Appendix E Data for Investigation 18-8

Stations	Surface Elevations	Rock Description From Surface Downward				
		Layer I	*Layer II*	*Layer III*	*Layer IV*	*Layer V*
1	248 meters	weathered gray outwash (2 meters)*	unweathered gray outwash (2 meters)	weathered red outwash (7 meters)	bedrock	
2	246 meters	weathered gray outwash (2 meters)	unweathered gray outwash (2 meters)	weathered red outwash (7 meters)	bedrock	
3	250 meters	weathered gray outwash (2 meters)	unweathered gray outwash (3 meters)	weathered red till (4 meters)	bedrock	
4	270 meters	weathered gray till (3 meters)	unweathered gray till (15 meters)	weathered red till (7 meters)	bedrock	
5	272 meters	weathered gray till (2 meters)	unweathered gray till (15 meters)	weathered red till (7 meters)	soil (1 meter)	bedrock S grooves
6	276 meters	weathered gray till (3 meters)	unweathered gray till (20 meters)	weathered red till (7 meters)	bedrock S grooves	
7	264 meters	weathered gray till (2 meters)	unweathered gray till (5 meters)	bedrock SW grooves		
8	264 meters	weathered gray till (1 meter)	unweathered gray till (3 meters)	bedrock SW grooves		

*thickness of layer

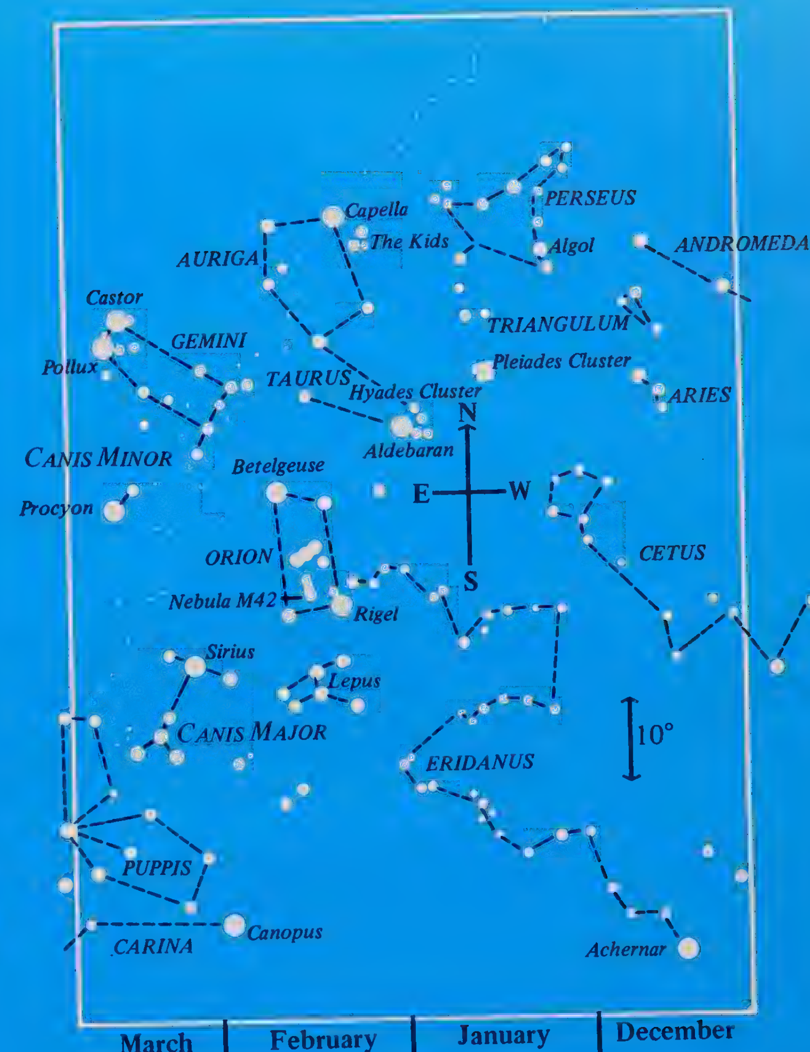
Appendix F Astronomical Data

F-Part 1 Star and Constellation Charts Hold overhead so arrows point to directions on horizon.



Northern Hemisphere

Big Dipper
URSA MAJOR
N
E
W
S
Arcturus
LEO
CANCER
Beehive Cluster
Castor
Pollux
GEMINI
Regulus
CANIS MINOR
Procyon
VIRGO
Spica
CRATER
HYDRA
CORVUS
10°
Sirius
CANIS MAJOR
CENTAURUS
Globular Cluster
VELA
PUPPIS
CRUX
CARINA
Canopus
June
May
April
March



Capella
The Kids
PERSEUS
Algol
ANDROMEDA
AURIGA
Castor
GEMINI
Pollux
TRIANGULUM
Pleiades Cluster
TAURUS
Hyades Cluster
ARIES
CANIS MINOR
Aldebaran
N
Betelgeuse
E
W
S
Procyon
ORION
CETUS
Nebula M42
Rigel
Sirius
Lepus
CANIS MAJOR
10°
ERIDANUS
PUPPIS
Canopus
CARINA
Achernar
March
February
January
December

F-Part 2
Physical Properties of the Planets

Characteristics	Mercury	Venus	Earth	Moon	Mars	Jupiter	Saturn	Uranus	Neptune	Pluto
diameter‡	0.38	0.96	1.0	0.27	0.53	11.2	9.5	3.7	3.5	1.0
volume‡	0.06	0.88	1.0	0.02	0.15	1,318	769	50	42	1.0
mass‡	0.05	0.81	1.0	0.01	0.1	318	95	1.5	17	?
surface gravity‡	0.4	0.9	1.0	0.16	0.4	2.6	1.1	1.0	1.5	?
orbital period‡	0.24	0.62	1.0	—	1.9	11.9	29.5	94	164.8	248
spin period‡	58	243*	1.0	27.3	1.0	0.41	0.43	0.45	0.65	?
mean distance from sun‡	0.39	0.72	1.0	1.0	1.52	5.2	9.54	19.18	30.07	39.44
mean density	5.4	5.1	5.5	3.3	4.0	1.3	0.7	1.6	2.25	?
number of satellites	0	0	1	0	2	12	10	5	2	0
maximum magnitude	−0.2	−4.2	—	−12.7	−2	−2.5	−0.7	5.5	7.9	14.9
average temperature in °K	960	600	287	300	285†	135	120	90	?	?
observed components of atmosphere		CO_2	N_2, O_2, H_2O, CO_2		N_2, H_2O, CO_2	H_2, NH_3, CH_4	NH_3, H_2, CH_4	CH_4, H_2	CH_4, H_2	none

*retrograde †warmest portion ‡ earth = 1

F-Part 3
Nearest and Brightest Stars

The 20 Brightest Stars

Star	Temperature in °K	Number of Times the Sun's Luminosity	Distance in Light Years
SIRIUS	10,000	23	8.6
CANOPUS	7,400	1,500	100
ALPHA CENTAURI A	5,800	1.3	4.3
ARCTURUS	4,500	90	36
VEGA	10,700	60	26
CAPELLA	5,900	150	47
RIGEL	11,800	40,000	800
PROCYON A	6,500	7.6	11.4
BETELGEUSE	3,200	17,000	500
ACHERNAR	14,000	200	65
BETA CENTAURI	21,000	3,300	300
ALTAIR	8,000	10	16.5
ALPHA CRUCIS	21,000	2,700	400
ALDEBARAN	4,200	90	53
SPICA	21,000	1,900	260
ANTARES	3,400	4,400	400
POLLUX	4,900	3,300	29
FOMALHAUT	9,500	14	23
DENEB	9,900	40,000	1,400
BETA CRUCIS	22,000	6,000	500
(SUN	5,600	1	0.00002)

The 21 Nearest Stars

Star	Temperature in °K	Number of Times the Sun's Luminosity	Distance in Light Years
SUN	5,600	1	0.00002
ALPHA CENTAURI A	5,800	1.3	4.3
ALPHA CENTAURI B	4,200	0.36	4.3
ALPHA CENTAURI C	2,800	0.00006	4.3
BARNARD'S STAR	2,800	0.00044	5.9
WOLF	2,700	0.00002	7.6
LALANDE 21185	3,200	0.0052	8.1
SIRIUS A	10,400	23	8.6
SIRIUS B	10,700	0.008	8.6
LUYTEN 726–8A	2,700	0.00006	8.9
LUYTEN 726–8B	2,700	0.00004	8.9
ROSS 154	2,800	0.0004	9.4
ROSS 248	2,700	0.00011	10.3
EPSILON ERIDANI	4,500	0.30	10.7
ROSS 128	2,800	0.00033	10.8
LUYTEN 789–6	2,700	0.00012	10.8
61 CYGNI A	4,200	0.083	11.2
61 CYGNI B	3,900	0.040	11.2
PROCYON A	6,500	7.6	11.4
PROCYON B	7,400	0.0005	11.4
EPSILON INDI	4,200	0.13	11.4

Acknowledgements

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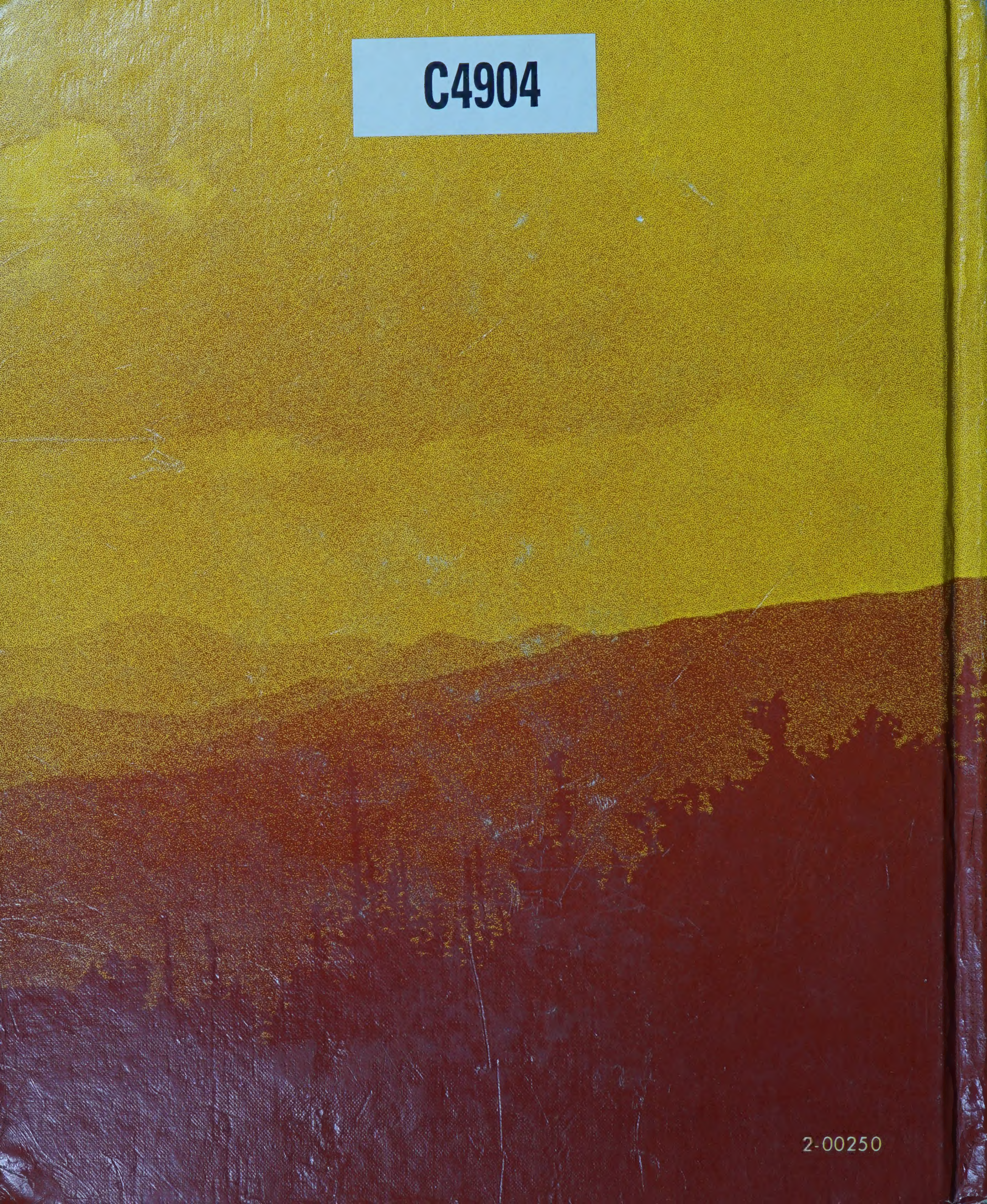

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